LOWER LEG COMPRESSION SLEEVES: INFLUENCE ON RUNNING MECHANICS AND ECONOMY IN HIGHLY TRAINED DISTANCE RUNNERS

by
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ABSTRACT

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Athletes in a number of sports are using compression as a means to improve training, performance, and recovery. However, the efficacy of and mechanisms behind the use of lower leg compression as an ergogenic aid to improve running performance is unknown. **Purpose:** To examine whether or not wearing moderate lower leg compression sleeves during exercise evokes changes in running economy due to altered gait mechanics. **Methods:** Sixteen highly trained male distance runners completed two separate running economy (RE) tests during a single session, a treatment trial of calf compression sleeves and a control trial without compression sleeves. RE was determined by measuring oxygen consumption at three constant submaximal speeds of 233, 268, and 300 $m \cdot min^{-1}$ on a motorized treadmill. Variables related to running mechanics were measured during the last 30 seconds of each four-minute stage of the RE test via wireless tri-axial 10g accelerometer devices attached to the top of each shoe. Values of ground contact time, swing time, stride time, stride frequency (SF), and stride length (SL) were determined from accelerometric output corresponding to foot strike and toe-off events obtained from a minimum of 25 consecutive steps. Statistical significance was set at $P < 0.05$. **Results:** There were no significant differences in submaximal VO_2 between control and treatment trials at any of the speeds. Additionally, there was no significant difference in the slope of the lines relating submaximal VO_2 and running speed between the two experimental conditions. There were no significant differences in ground contact time, swing time, stride time, stride frequency, and stride length between control and treatment conditions at any of the running speeds. However, there was a large inter-individual variability in response to compression, and three subjects exhibited large, consistent reductions in VO_2 at each speed with compression treatment. These three subjects demonstrated the greatest decreases in SL and SF variability with compression. **Conclusions:** Wearing lower leg compression does not significantly change running mechanics or oxygen consumption while running at submaximal speeds. However, the individual metabolic and gait response to wearing lower leg compression varies greatly.

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CHAPTER 1

INTRODUCTION

Through the decades, endurance athletes, elite and novice alike, have tried everything from bulls' testicles to erythropoietin (EPO) to Viagra in a desperate, and often illegal, effort to gain an advantage. Recently, lower leg compression sleeves have gained popularity as a promising, but still legal, method for improving performance. Compression stockings, often seen in long-distance running and ultra-endurance events, allegedly improve performance. The claims range from increasing blood flow and oxygen delivery to the lower leg to reducing lactic acid accumulation to increasing energy (Friel, 2007; Kelly, 2005; Revel Sports®, 2009; Sagal, 2009). However, the mechanism for the proposed performance enhancement of lower leg compression sleeves has yet to be determined.

One possible mechanism of compression sleeve action may be in the alteration of running mechanics. A moderate compression stocking could significantly alter lower leg mechanics, such as leg stiffness or ground contact time, ultimately resulting in changes in energy return from the ground or running economy. Running economy is defined as the energy demand for a given velocity of submaximal running, measured via steady-state consumption of oxygen (Saunders, Pyne, Telford & Hawley, 2004). Running economy plays a central role in distance running performance, and research supports a relationship between running mechanics and economy (Williams & Cavanagh, 1987). However, it is not known whether a potential change in the gait mechanics associated with lower leg compression would result in changes in running economy. It was the nature of this question that prompted the current investigation.

Statement of the Problem

The problem of the study was that there is a lack of research exploring the efficacy of and mechanisms underlying the use of lower leg compression as an ergogenic aid for running performance.

Purpose of the Study

The purpose of the study was to examine whether wearing moderate lower leg compression sleeves evokes changes in running economy due to altered gait mechanics.

Justification for the Study

The distance running boom began in the late 1960s, and since then the number of runners in America has continued to grow extensively. The National Sporting Goods Association estimated that nearly 25 million U.S. residents ran six or more times in 2002. Furthermore, according to data received by USA Track & Field, nearly 10.5 million runners ran 100 days or more in 2002, while more than 11 million runners have been in the sport for 10 or more years. The increase in popularity of distance running is not limited to recreational jogging; rather, more and more athletes are turning to competitive running. In just one year (from 2001 to 2002), participation in road races from the mile to the marathon showed significant growth (USATF, 2002). With the rise of competitive running comes a subsequent increased interest in improving performance.

Recently, athletes in a number of sports are using compression garments as a means to improve training, performance, and recovery. However, science has yet to show the specific mechanistic or physiological effects of compression during exercise. Very few studies have looked at the effects of compression during and after running in particular.

Graduated compression stockings have been used in the clinical setting for many years to: (1) increase deep venous velocity; (2) reduce venous pooling; and (3) improve venous return. The medical success of compression prompted some exercise scientists to question whether this same method would improve venous return during and after exercise – resulting in a greater clearance of metabolites. Subsequent research has demonstrated a decrease in blood lactate when wearing the compression stockings during exercise, suggested to be the result of lactate being retained in the muscle versus entering the bloodstream (Berry & McMurray, 1987). Ali, Caine, & Snow (2007) measured heart rate, ratings of perceived exertion, ratings of soreness, and performance during intermittent and continuous running and found that wearing the compression stockings resulted in reduced delayed-onset muscle soreness after the continuous (10 kilometer) run. More recently, Kemmler et al. (2009) showed improved measures of running performance with compression treatment. To date, no other studies have investigated the effects of compression with running.

In theory, compression could change muscle stiffness and joint mechanics, thereby having an ergogenic effect. Preliminary observations by our laboratory have indicated that wearing lower leg compression sleeves reduces ground contact time and may have an effect on other mechanical variables. Research has shown that the oxygen cost of running at submaximal workloads (i.e., running economy) is influenced in large by individual differences in running mechanics. First, it is important to note the strong relationship between running economy and distance running performance. Particularly at the elite level, where all athletes possess a high VO_{2max} and can sustain performance at a high percentage of VO_{2max} for a long period of time, small differences in running economy often determine the outcome performance (Foster & Lucia, 2007). Thus, any change in running mechanics that influences running economy could ultimately affect an athlete's performance.

Several studies have attempted to characterize the biomechanics of elite and economical distance runners via analysis of mechanical power, anthropometric dimensions, postural effects, gait patterns, kinematics, kinetics, muscle contractions, training, gender, age, shoes, and environmental factors (Anderson, 1996). Of particular interest to the current study are differences in gait patterns between economical and less-economical running. Hoyt et al. (1994) found that the metabolic cost of locomotion is determined by the cost of supporting body weight and the rate at which this force can be generated (i.e., time during which the foot is in contact with the ground) (Hoyt, Knapik, Lanza, Jones &

Staab, 1994). Other research has shown that an increase in stiffness of the lower extremity is associated with improved running economy (McMahon, Valiant & Frederick, 1987; Butler, Crowell & Davis, 2003). It appears that increased stiffness allows greater use of stored elastic energy. However, research also shows that changing vertical spring stiffness will change the contact period (McMahon et al., 1987), with greater stiffness shortening ground contact time. It is unknown whether lower leg compression sleeves alter stiffness and gait mechanics and, if so, what impact this alteration will have on running economy.

Limitations

The results from this investigation were interpreted considering the following limitations:

1. The participants in the research study were not a random sample; subjects were experienced runners who volunteered to participate in this study.
2. The sample size of this study was small (N=16) necessitating caution in extrapolation of the data to a larger population.
3. The subjects' current state of training may have impacted the validity of the study.
4. The study was nonblind; thus, any differences obtained with compression treatment may have been at least partially dependent on motivation of the subjects.

Delimitations

This study was delimited to the following:

1. Sixteen highly trained male distance runners, who were free of any injury or illness that would impair normal training and racing within the two weeks prior to the study.
2. Operationalized definitions regarding ground contact time, swing time, stride length, stride frequency, leg stiffness and submaximal oxygen consumption.

3. Counterbalancing of with compression sleeve (T) and without compression sleeve (C) sessions.
4. Subjects completed a pre-testing questionnaire regarding experience and beliefs about compression garments to identify any bias within the population.
5. The use of a research-grade treadmill, computer interfaced, open flow, indirect calorimetry system, motion capture system, accelerometry, and DasyLab software to measure the desired variables.
6. The use of SPSS to analyze the data.
7. The study was conducted for a period of four months between June and September 2009.

Assumptions

The study was based upon the following assumptions:

1. Running economy can be altered.
2. Running economy influences distance running performance.
3. Subjects are familiar with running on a treadmill.

Hypotheses

The study was designed to test the following null hypotheses:

1. There is no significant change in running economy when running with lower leg compression sleeves.
2. Lower leg compression sleeves do not significantly alter the following gait variables: ground contact time, swing time, stride length, stride frequency, and leg stiffness when running.

Definition of Terms

For consistency of interpretation, the following terms are defined:

Efficiency. Work done divided by energy expended. Specifically, *muscular efficiency* is mechanical work done divided by total metabolic energy expended (Cavanagh & Kram, 1985).

Ergogenic aids. External forces that increase capacity for bodily or mental labor, especially by eliminating fatigue (www.dictionary.com).

Ground contact time (t_c). The time (in s) from when the foot contacts the ground to when the foot toes-off (i.e. breaks contact with the ground) (Weyand, Sternlight, Bellizzi, & Wright, 2000).

Kinematics. Branch of biomechanics concerned with describing the motion of bodies, including such measures as how far, how fast, and how consistently (Hay, 1993).

Kinetics. Branch of biomechanics concerned with describing what causes a body to move the way it does (Hay, 1993).

Leg stiffness. The relationship between the deformation of a body and a given force, estimated from measurements of mass, ground contact time and flight time, reported in KiloNewtons per meter (Butler et al., 2003; Hobara, 2009).

Running economy. The energy demand for a given velocity of submaximal running, measured via steady-state consumption of oxygen (Saunders et al., 2004*a*).

Stride frequency. The number of ground contact events (i.e. steps taken) per minute (Cavanagh, Pollock & Landa, 1977).

Stride length. The length (in m) from toe-off to ground contact in successive steps, calculated from stride frequency and treadmill speed (Weyand et al., 2000).

Swing time (t_{sw}). The time (in s) from toe-off to ground contact of consecutive footfalls of the same foot (Weyand et al., 2000).

Vertical oscillation (VOSC). Range of vertical oscillation of the center of mass from maximum to minimum during the running cycle (Williams & Cavanagh, 1987).

CHAPTER 2

REVIEW OF THE RELATED LITERATURE

Recently, lower leg compression sleeves have gained popularity as a promising method for improving distance running performance.   However, the mechanism for the proposed performance enhancement of lower leg compression sleeves is yet unknown; research regarding the effects of lower leg compression has been focused primarily in the clinical setting. One possible mechanism of compression sleeve action may be in the alteration of running mechanics. Research supports a relationship between running mechanics and running economy, which has been described as the single most important component of distance running performance (Saunders et al., 2004*a*). As a result, improving running economy has been the focus of a number of studies, with varying degrees of success. These efforts have been based on the idea that an individual's running economy is the result of one or more of the following: training, environment, anthropometry, physiology, and biomechanics. Of particular interest to the present study are the biomechanical characteristics of the most economical and preeminent distance runners.

In the context of the present investigation, this review will focus on literature related to improvements in running economy, particularly through changes in biomechanical variables. The review is presented in the following manner: (1) the relationship between running economy and endurance performance, (2) improving running economy, (3) biomechanical factors associated with economical running, (4) altering running mechanics, (5) leg compression garments – clinical and performance implications, and (6) summary.

Running Economy and Endurance Performance

Successful distance running depends on a complex combination of physiological factors (Foster & Lucia, 2007). Traditionally, maximal oxygen consumption (VO_{2max}) was regarded as the most important component of distance running performance. High VO_{2max} is itself dependent upon a number of variables, including high cardiac output and oxygen delivery to working muscles. The ability to sustain a high percentage of VO_{2max} (fractional utilization of VO_{2max}), with minimal accumulation of lactic acid (high lactate threshold), has also been implicated as an important determinant of successful distance running (Costill, Thomason & Roberts, 1973). The third component of distance running performance is running economy (RE), i.e., the oxygen cost of running at a given speed. It is important to first make the distinction between two commonly used terms: economy and efficiency. Often the two are used interchangeably in the lay community (and occasionally in scientific literature, as well). The term efficiency, though defined simply as work done by energy expended, cannot so easily be determined. Muscular efficiency has components that have not yet been determined, including changes in physiological maintenance during work, fraction of mechanical work stored elastically, transferred and reutilized, and differences in positive and negative work. Conversely, the term economy is both "conceptually clear and practically useful for evaluation of performance in endurance activities" (Cavanagh & Kram, 1985). Running economy is defined as the energy demand for a given submaximal velocity, measured via steady-state oxygen consumption, with lower oxygen consumption at a given velocity indicating greater running economy (Saunders et al., 2004*a*).

Not surprisingly, there is a strong association between running economy and distance running performance (Saunders et al., 2004*a*). In fact, RE has been shown to be a better predictor of endurance performance than maximal oxygen uptake (VO_{2max}) in elite runners with similar VO_{2max} values. Figure 1 (Saunders et al., 2004*a*) illustrates the importance of RE to distance running performance in comparison to other variables.

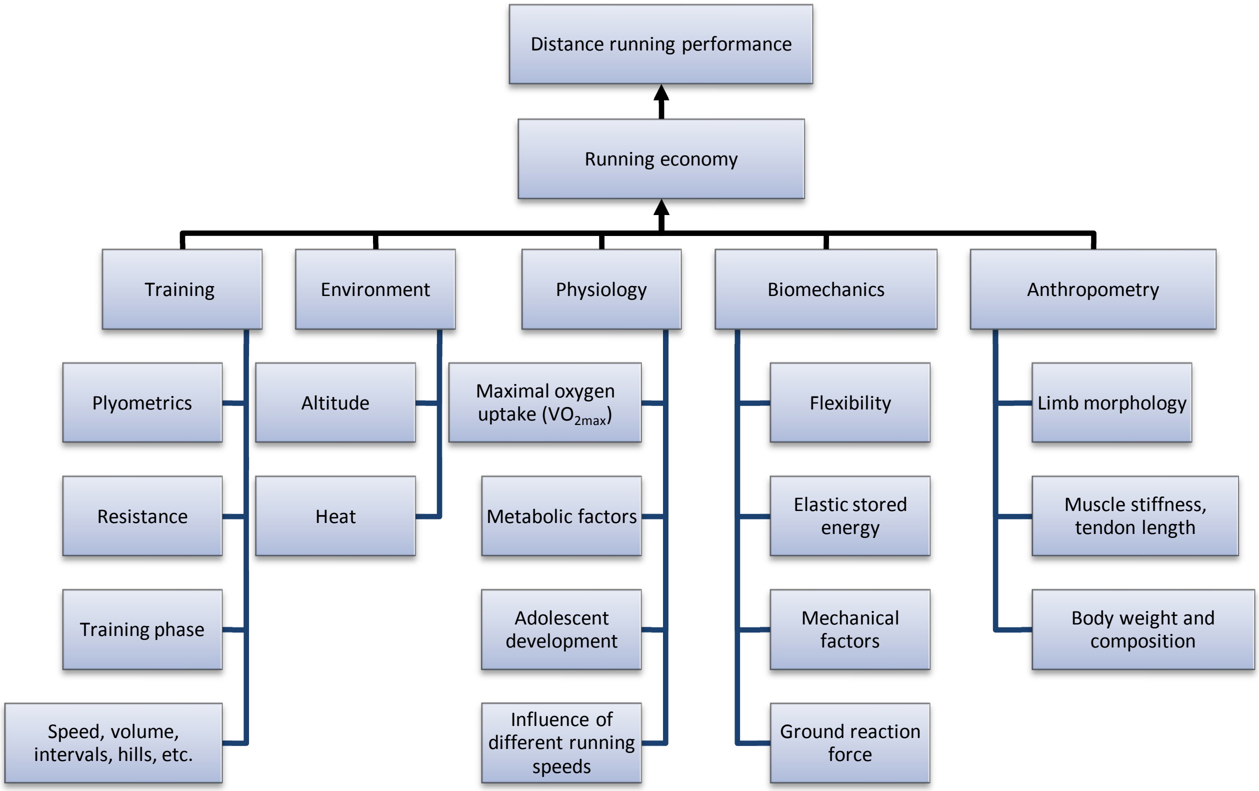


Figure 1. Factors affecting running economy (adapted from Saunders et al., 2004*a*).

A study by Costill et al. (1973) was one of the first to acknowledge the importance of running economy in distance events. Sixteen highly trained runners of varying abilities performed maximal and submaximal treadmill runs and later competed in a 10-mile road race (to obtain non-laboratory running performance data). The results demonstrated that distance running performance could be accurately estimated from submaximal and maximal data; for example, a significant correlation (r=0.94) between the $\%VO_{2max}$ at the submaximal speed of 268 $m{\cdot}min^{-1}$ and the 10-mile running time was noted. However, the investigators suggest that focusing solely on submaximal VO_2 may not be an effective means to differentiate between distance running abilities; this may be due to the large range of running abilities in the study's subjects. Later research, utilizing nationally-prominent highly trained distance runners of comparable abilities, showed strong correlations (r=0.79-0.83) between submaximal VO_2 and distance running ability (Conley & Krahenbuel, 1980). Subjects averaged 32.1 minutes on a 10-kilometer run, 71.7 $ml \cdot kg^{-1} \cdot min^{-1}$ for VO_{2max}, and 44.7, 50.3, and 55.9 $ml \cdot kg^{-1} \cdot min^{-1}$ for steady-state oxygen consumption at three running speeds (241, 268, and 295 $m \cdot min^{-1}$). There was no significant relationship between VO_{2max} and running performance (p=0.35); however, the relationships between submaximal VO_2 at the different treadmill speeds and 10k time were r=0.83, 0.82, and 0.79, respectively, indicating that within a homogenous, highly-trained group running economy accounts for a significant portion (65.4%) of variation in performance.

Pollock (1977) investigated the possibility of differentiating elite runners into types (i.e. marathon, middle-long distance) via their submaximal and maximal metabolic characteristics. Subjects included 20 elite distance runners, eight "good" distance runners, and ten untrained lean college students; the elite runners were further divided into marathon runners and middle-long distance runners. Subjects performed maximal and submaximal treadmill tests (though, the untrained runners did not perform the submaximal test due to their inability to sustain the same speed as the other runners). The elite runners had significantly better running economy than the good runners (the untrained runners were unable to complete the submaximal testing). At a speed of 10 miles per hour, elite and good runners had average VO_2 values of 53 and 56 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively, and at 12 mph they averaged 64 and 66 $ml \cdot kg^{-1} \cdot min^{-1}$. In addition, the VO_{2max} of the middle-long distance group was significantly higher than the marathon group; however, the marathon runners had significantly lower submaximal VO_2 values, indicating better running economy.

East African distance runners are a prime example of the importance of running economy in endurance performance. Athletes of East African origin (e.g., Kenyans, Ethiopians) have dominated most endurance-running events in international competition for the past few decades. Early research by Saltin et al. (1995) showed superior running economy in Kenyan runners when compared to Scandinavian runners. The study compared Kenyan junior and senior runners with Scandinavian runners, including untrained boys of each ethnicity. The best Scandinavian runners were not significantly different from the Kenyan runners in VO_{2max}, but the oxygen cost for a given running speed was lower in the Kenyan runners, thus demonstrating better running economy. Other studies and reviews have since supported this conclusion that East Africans' high aerobic capacity and good running economy make them superior runners (Weston, Karamizrak, Smith, Noakes & Myburgh, 1999; Larsen, 2003). Lucia et al. (2006) investigated possible explanations for the recent success of Eritrean runners. Eritrea, like Kenya and Ethiopia, is an East African country, yet it lacks the long-standing distance running tradition inherent in the other nations. The study compared anthropometric and physiological characteristics of elite black Eritrean distance runners with elite white Spanish distance runners. The two groups had similar VO_{2max}, but the Eritreans exhibited better running economy. The running economy values for the Eritreans in this study were some of the best ever reported in the literature, giving rise to some doubt on the accuracy of the measurements. However, RE of the Spanish runners was comparable with values previously reported for elite, white distance runners. The African athletes had lower body mass index (BMI) and calf circumference and longer shank measurements than their Spanish counterparts. The investigators suggested the superior RE may be due to these anthropometric differences. Interestingly, the Eritreans also had shorter training histories, lower training volumes, and lower training speeds than the Spaniards, suggesting that high training volumes are not a prerequisite for achieving good running economy. Finally, it is important to note that Eritreans live at an altitude of about 2600 meters, higher than the typical training altitude for both other East African and white distance runners, which may have independently impacted running economy.

Foster and Lucia's conference review paper (2007) addressed three important questions: (a) *What is the range in running economy across the range of serious runners?* The authors stated that to compare running economy values across studies researchers commonly extrapolate oxygen consumption to a reference velocity of 268 $m \cdot min^{-1}$. At this speed, the average elite runner has a VO_2 of about 54 $ml \cdot kg^{-1} \cdot min^{-1}$, though the lowest reported value is 39 $ml \cdot kg^{-1} \cdot min^{-1}$ (an East African runner). (b)

Are the differences in running economy based on anatomical differences? It appears that there is a tendency for runners of small size and with small lower limbs to be the most economical. However, the hypothesis that running economy is dependent on body dimensions has not been confirmed. (c) *Can running economy be improved?* Despite relatively few studies of strategies to improve running economy, some evidence does exist to support the idea that economy can be improved through training interventions.

From the previous literature it is clear that success in distance running depends on running economy. In fact, it has been reported that a 5% increase in running economy results in an approximately 3.8% increase in distance running performance (Di Prampero et al., 1993). For a 28-minute 10k runner, this could amount to a drop of 63 seconds…an Olympic record time. As Foster and Lucia (2007) concluded, since high level athletes already possess a high VO_{2max}, whether through training or talent, as well as the ability to sustain performance at a high percentage of VO_{2max}, any future improvements in running performance will depend on improved economy.

Improving Running Economy

Improving running economy has been the object of a number of studies, which have been met with varying degrees of success. In recreational athletes, training has been shown to improve running economy, particularly during the initial phases of training (Beneke & Hutler, 2005). Other research, however, has shown the opposite effect – significantly worse running economy after training (Lake & Cavanagh, 1996). Explosive-strength training and biofeedback and relaxation techniques appear to have a positive effect on running economy (Paavolainen, Häkkinen, Hämäläinen, Nummela & Rusko, 1999; Storen, Helgerud, Stoa & Hoff, 2008; Caird, McKenzie & Sleivert, 1999), whereas, research exploring the results of core training and arm carriage retraining has shown no effect (Stanton, Reaburn, & Humphries, 2004; White, 2008). Altitude training has produced data sets showing both an improvement in RE (Katayama et al., 2004; Saunders et al., 2004*b*), no change in RE (Levine & Stray-Gundersen, 1997; Bailey et al., 1998; Truijens et al., 2007), and a slight worsening of RE (Stray-Gundersen, Chapman, & Levine, 2001; Laymon, Lundgren, McKenzie, Wilhite, & Chapman, 2009).

Beneke and Hutler (2005) conducted a longitudinal intervention of an eight-week specifically-designed training program with 16 recreational male athletes. Half of the subjects were designated to the training group and ran three to five times per week, beginning at an intensity of 50% of the heart rate (HR) reserve and progressively increased to 60-75% HR reserve, and the remainder of the subjects (n=8) served as controls, not participating in the training intervention. Before the training program (W0), the running economy of each participant at a "slow" (corresponding to a blood lactate concentration of 3.0 $mmol{\cdot}L^{-1}$) and "fast" (corresponding to the highest velocity that could be maintained for 3.0 minutes) speed was determined. The VO_2 at these two speeds was measured again after week four (W4) and week eight (W8). With the training program the experimental group significantly decreased their energy cost of running ($J{\cdot}kg^{-1}{\cdot}m^{-1}$) from 4.1 (W0) to 3.7 (W4 and W8) at the slower speed. During W4 and W8 at the faster speed there was no difference in the economies between the two groups until the second phase, where the runners continued until exhaustion. At this point subjects in the training group had higher energy costs of running (W4: 4.0 control versus 4.3 training; W8: 4.0 control versus 4.6 training), most likely due to the fact that they were able to continue running for a significantly longer period of time. The study showed that training can improve running economy, but it requires training specific for a desired running velocity. Furthermore, the effect is higher during the initial phase of training, as evidenced by the fact that there was no further improvement in economy in the training group at submaximal effort between weeks four and eight. Running performance may continue to improve, as seen in the increased time to exhaustion, but this is probably due to metabolic adaptations without any changes in running economy.

Lake and Cavanagh (1996) also examined the effect of running training on running technique and economy. Subjects (n=17) were untrained males who were able to run comfortably for 30 minutes at a speed of 202 $m \cdot min^{-1}$. Subjects were assigned to either a training (n=9) or non-training control group (n=8). Training consisted of six weeks of overground running, gradually increasing in frequency, intensity and distance. Before and after training the following kinematic and physiological variables were measured: a) vertical oscillation (cm), b) shank angle at footstrike (deg), c)trunk angle averaged throughout running cycle (deg), d)range of trunk lean throughout cycle (deg), e) maximal ankle plantarflexion near toe-off (deg), f) maximal knee flexion during support phase (deg), g) maximal and submaximal oxygen consumption ($ml \cdot kg^{-1} \cdot min^{-1}$), and h) heart rate (bpm). They found no differences in any kinematic variables between the training and control groups over time. Running performance, VO_{2max}, and measures of relative exercise intensity significantly improved in the experimental group; while running economy became significantly worse with training. The authors speculated that the worsened running economy may be due to the relatively short duration of the training intervention or a "time-course phenomenon." This refers to the idea that the initial large increase in maximal oxygen consumption with training is associated with a corresponding increase in submaximal VO_2. During the early stages of training, the increase in VO_{2max} is probably the most important factor in improved running performance; whereas after VO_{2max} is close to a plateau, further increases in performance are due to improvements in economy.

In summary, the literature indicates that the potential for improving running economy exists; however, it is important that the appropriate interventions and target variables are chosen.

Biomechanical Factors Associated With Economical Running

One way to improve running economy may be through the alteration of running mechanics. Previous research supports a relationship between running mechanics and economy. Several studies have attempted to characterize the biomechanics of elite and economical distance runners via analysis of mechanical power, anthropometric dimensions, postural effects, gait patterns, kinematics, kinetics, muscle contractions, training, gender, age, shoes, and environmental factors (Anderson, 1996).

Of particular interest to the current study are (a) differences in gait patterns between economical and less-economical runners, and (b) effects of ground contact time and leg stiffness on running economy. Some of the earliest research comparing the biomechanical characteristics of elite and non-elite runners showed that elite runners had better running economy, less vertical oscillation, shorter absolute and relative stride length, and better body symmetry while running (Cavanagh et al., 1977). They filmed “good” (n=8, mean 3-mile time 15:16.7, marathon 2:34:40) and “elite” (n=14, 3-mile 13:10.2, marathon 2:15.52) distance runners while they ran on a treadmill at four steady speeds between 4.96 and 6.44 $m \cdot s^{-1}$. The speeds were presented in ascending order, and approximately 10 strides were filmed during each condition. One limitation to above study is the fact that when it was carried out, treadmills were not commercially available to the extent that they are today; thus, treadmill acclamation may have impacted performance, gait characteristics, and/or running economy. It is likely that the subjects who were deemed “good” runners were those less familiar with treadmill running, which may have affected their gait characteristics during testing. The authors acknowledged that their study did not answer the question of whether efficient running is a function of good style, subcellular biochemistry, or a weighing of both, as well as what other factors are important. They suggest using the technique of multiple regression analysis to identify which of the many variables are important for efficient running.

One decade later, Williams and Cavanagh (1987) investigated the relationship between distance running mechanics, running economy, and performance. A variety of kinetic, kinematic, and physiological measures were obtained for 31 actively training runners running at 3.6 $m \cdot s^{-1}$, and a subset of 16 runners was also evaluated in regards to their performance in a 10-kilometer run. Physiological measures included maximal and submaximal oxygen consumption, muscle fiber composition, and the ability to store and return elastic energy during knee bends. The chosen speed was appropriate for the subjects in the study but is relatively slow for highly trained and elite distance runners; thus, results may not entirely apply to more trained runners. A multiple regression analysis was used to evaluate the overall relationship between biomechanics and running economy, with VO_2 as the dependent variable. A factor analysis was used to select a smaller number of variables (from the many the investigators collected) to be included in the regression. The results indicate that more economical runners tend to have identifiable patterns in their running mechanics. Vertical ground reaction forces were lower, shank, trunk and plantar flexion angles were greater, and minimum knee velocity was lower in the most economical group of runners. A number of other variables had consistent, but not significant, trends between groups separated on the basis of $VO_{2submax}$, including less arm movement, less vertical oscillation, and a tendency towards a "rearfoot" strike. The multiple regression analysis indicated that 10k times correlated highest with slow-twitch muscle percentage and VO_{2max} (r=-0.88 and -0.76, respectively). Overall, of the variables submitted to the multiple regression analysis of biomechanical variables on submaximal oxygen consumption, three (shank angle at footstrike, maximal plantar flexion angle, and net positive power) were retained to give an overall R^2=0.54. The multivariate analysis performed on the original variables across the economy groups was significant. The authors concluded that no single variable can explain differences in economy but rather economy is related to a weighted combination of the influences of many variables.

Elite distance runners often exhibit shorter ground contact time than their non-elite counterparts, accomplished primarily by increasing ground reaction forces (Weyand, Sternlight, Bellizzi, & Wright, 2000; Bushnell & Hunter, 2007). Unfortunately, generating greater ground reaction forces comes at the price of increased metabolic energy expenditure and the potential for premature fatigue. Kram and Taylor (1990) reported an inverse relationship between the rate of energy used while running and the time the foot applies force to the ground during a single stride. They measured steady state oxygen consumption and average foot contact time over a range of speeds in kangaroo rats (32 g), ground squirrels (210 g), spring hares (3.0 kg), dogs (25.8 kg), and ponies (141 kg), hypothesizing that larger animals with longer legs and step lengths would have lower costs of locomotion. The results showed that the cost of running, regardless of speed, was primarily dependent on the cost of supporting the animal's weight and the time course of generating this force. However, all of the animals tested in this study were quadrupeds, so it was unknown whether the results would be applicable to human locomotion. Hoyt et al. (1994) developed an electronic foot contact monitor that would allow estimation of metabolic energy expenditure during locomotion (M_{loco}). The investigators compared data from the ambulatory foot contact monitor with measures of energy expenditure calculated via indirect calorimetry. The equation used with the foot monitor,

$$M_{loco} = 3.702*(\text{body weight/ground contact time})-149.6 \qquad [1]$$

was strongly correlated with laboratory measures of energy expenditure (r^2=0.93) during both walking and running.

Other research has shown that an increase in stiffness of the lower extremity is associated with improved running economy (McMahon et al., 1987; Gleim, Stachenfeld, & Nicholas, 1990; Butler et al., 2003; Dalleau, Belli, Bourdin, & Lacour, 1998). It appears that increased stiffness allows greater use of temporarily stored elastic energy. More specifically, the elastic energy stored when stretching contracted muscles (i.e., the eccentric portion of the support phase during running) can be used as additional energy during the shortening of active muscles (i.e., the concentric portion of the support phase). Early research by Cavagna et al. (1964) concluded, after a number of calculations, that (1) efficiency in running is about 40-50%, (2) such a high value requires a substantial contribution of energy delivered at a low cost, (3) the low-cost energy appears to be elastic recoil energy, and (4) the elastic work contributes roughly half of the total mechanical work performed in running.

In a study of 100 subjects, the relationship of 11 measures of trunk and lower limb flexibility to walking and running economy was examined (Gleim et al., 1990). The "tightest" third had significantly lower submaximal oxygen consumption than the "loosest" third (9%, $p<0.05$), with the "normal" in between. The two measures of flexibility which gave the best separation between economy groups were trunk rotation and lower limb turnout. They speculated that these two measures were the best predictors of economy because stiffness in the trunk and lower limb limits excess motion in the transverse plane. However, no biomechanical analyses were conducted to confirm this hypothesis.

Dalleau et al. (1998) looked at the running movement in humans as an oscillating system consisting of a spring (the leg) and a mass (the body mass). Subjects ran on a treadmill at a high velocity (90% VO_{2max}) for four minutes, during which time body displacements were measured using a kinematic arm. Oxygen consumption, step frequency (via pressure sensors on shoes), and lactate concentrations were also measured. The energy cost of running and leg stiffness were found to be highly inversely correlated ($r= -0.80$). It is important to note that since the entire body was being modeled as a spring, the calculated stiffness value is the apparent stiffness of a spring, which represents the elasticity of the entire musculoskeletal system, including muscles, tendons and ligaments acting across joints.

Previous research also shows that changing vertical spring stiffness will change the contact period (McMahon et al., 1987), with greater stiffness shortening ground contact time. The investigators in this study had subjects run with exaggerated knee flexion, adopting a style of movement made famous by Groucho Marx (while walking). Subjects ran at a given speed with progressively deeper knee flexion, which resulting in corresponding increases in ground contact time. They found that running in this manner reduces the effective vertical stiffness, while also increasing the rate of oxygen consumption by up to 50%. These results conflict with the idea that shortening ground contact time increases metabolic energy expenditure. The relative contributions of greater stiffness and lower ground contact time have not been determined.

The previous literature supports a relationship between running mechanics and economy; thus, one approach to improving running economy may be via altering running mechanics.

Altering Running Mechanics

Gait retraining to evoke changes in running economy has not been well-studied. To date, gait retraining research has primarily been utilized within the clinical population for patients learning to walk again after injury or with disability. More recently, a technique known as real-time feedback (RTF) has emerged as a potential means of gait retraining. With RTF subjects are instantaneously informed of specific biological variables while performing a task. The complexity of RTF methods ranges greatly, from a simple elastic training harness (as used in the arm carriage study referenced previously) to a multifaceted virtual reality environment (Wilken, 2008). Like other methods of gait retraining, RTF has been explored primarily in the clinical setting for injury prevention or rehabilitation. Studies utilizing RTF for gait retraining within these populations have been successful in altering kinetic and kinematic variables (Crowell, Milner, Davis & Hamill, 2005; Pohl, 2008; Wilken, 2008). Davis (2008) demonstrated retention, up to one year post-training, of learned gait characteristics reducing tibial shock.

A small number of studies have specifically examined whether biomechanical training can affect gait economy and technique in non-clinical populations. Petray and Krahenbuhl (1985) gave five minutes of instruction per week to 10-year old boys regarding various aspects of running technique. The subjects were instructed to reduce unnecessary vertical displacement, become aware of their stride rate and stride length, and work on posture and relaxation. After an 11-week instruction program there were no significant improvements in running economy, stride length or vertical displacement. The short verbal instruction period was likely insufficient to elicit positive alterations in running mechanics, particularly if subjects did any running outside of the controlled environment. Similarly, Messier and Cirillo (1989) examined the effects of verbal and visual feedback on running technique, perceived exertion and running economy in female novice runners (n=22). The experimental subjects (n=11) received feedback before and during 15 20-minute treadmill running sessions over a period of five weeks (three days per week). The verbal feedback consisted of verbal cues from the investigator during the first and tenth minutes of the run reminding the subject of the mechanical flaws on which to focus. Each week of training was devoted to a particular aspect of running mechanics. Immediate visual feedback was provided during the first and last seven minutes of each session via a monitor connected to a video-tape recorder perpendicular to the subject's principal plane of motion; i.e., the subject was simply able to watch herself run. The control group (n=11) training sessions were of the same length and duration as the experimental, but with no feedback. However, to enhance subject-experimenter interaction, control subjects described their thoughts during two separate minutes of each session. The feedback had a significant effect on the experimental group's running technique, specifically longer strides, shorter support time, and increased knee flexion and ankle dorsiflexion. They also displayed significantly greater vertical movement of the center of mass, in contrast to the desired outcome. The authors speculate this was due to the increased non-support time while running at the same treadmill speed. The increase in vertical oscillation may have offset the potential gains in economy from the other biomechanical variables; overall, the investigators found no significant change in running economy. Furthermore, the short period of training may have prevented subjects from fully adapting to the new running style.

An investigation on stride length manipulation and racewalking economy found that highly-trained racewalkers select locomotion patterns that are nearly optimal in terms of aerobic demands (Morgan & Martin, 1986). Subjects (n=7) completed racewalking bouts at five randomly ordered stride length conditions, from -10 to +10% of their freely chosen stride length. Subjects' oxygen consumption steadily increased as their stride length deviated further from their freely chosen stride. More recently, Tseh, Caputo, & Morgan (2008) sought to determine if gait manipulation influences running economy by having recreational female runners (n=9) complete treadmill running sessions under four conditions, including normal running and three extreme running styles: a) hands behind back, b) hands on head, and c) exaggerated vertical oscillation (VOSC). Running with exaggerated VOSC required subjects to lightly touch a foam pad, located above them at a distance four times the standard deviation of baseline VOSC, with the top of the head. Hands on head and exaggerated VOSC both resulted in significant increases in submaximal oxygen consumption compared to the other two conditions. Researchers in these two studies were able to produce marked decrements in running economy with specific gait manipulations during an acute bout of exercise; however, no known studies have been found to improve running economy in this same manner.

Leg Compression Garments – Clinical and Performance Implications

Athletes in a number of sports are using compression as a means to improve training, performance, and recovery. Moderate compression may alter biomechanical characteristics; however, science has yet to show the specific mechanistic or physiological effects of compression during exercise. Very few studies have looked at the effects of compression during and after *running* in particular. Possible mechanisms of action include alteration of venous blood flow, improved deep tissue oxygenation, improved clearance of metabolites, and changes in elastic parameters.

Graduated compression stockings have been used for over 25 years in the clinical setting to increase deep venous velocity, reduce venous pooling, and improve venous return. Agu, Hamilton, and Baker (1999) reviewed relevant publications indexed in Medline (1966-1998) to report on the mechanism of action, design, efficacy and complications associated with graduated compression stockings in the clinical population, specifically in the prevention of venous thromboembolism. Deep vein thrombosis (DVT), or the formation of a blood clot in a deep vein, is a serious medical condition with potentially fatal outcomes. Compression stockings are designed to provide either graduated or uniform compression. Graduated compression, which gives the greatest pressure at the ankle and gradually decreases proximally up to the thigh (generally 18, 14, 8, 10, 8 mmHg distal to proximal), has been favored in the literature. The graduated compression stocking's mechanism of action appears to be multifactorial; a decrease in venous dilation, increase in flow velocity, improvement in valve function and increase in tissue factor pathway inhibitor could all contribute to decreases in venous thrombogenesis.

Agu, Baker, and Seifalian (2004) investigated the mechanism of action of graduated compression stockings by using near-infrared spectroscopy (NIRS) in patients with chronic venous insufficiency at rest, while standing, while performing a tiptoe exercise, and during light walking. Measures were taken in each subject without and with graduated compression (classes I to III). The subjects' venous function was assessed by measuring changes in hemoglobin (Hb) during the test, and muscle oxygenation was assessed by the oxygenation index, which is the difference between tissue oxyhemoglobin (HbO^2) and Hb. They found that while walking HbO^2 was significantly increased in subjects wearing the class III graduated compression stockings. Hemoglobin concentrations, however, decreased progressively from no-compression to higher grades of compression in all tests. The authors concluded that "in patients with venous insufficiency, graduated compression stockings may achieve their beneficial effects by reducing venous pooling and improving deeper tissue oxygenation."

The medical success of compression prompted some exercise scientists to question whether this same method would cause improvement in venous return during and after exercise – resulting in a greater clearance of metabolites. Preliminary investigations in the laboratory of Berry and McMurray (1987) indicated that graduated compression stockings significantly reduced exercise and recovery venous lactate levels. They sought to determine the mechanism behind the reduced lactate levels by setting up two experiments. The first measured maximal oxygen consumption, time to exhaustion, and blood lactate during and after a treadmill VO_{2max} test with and without compression stockings. The second evaluated the retention of lactate at the end of high-intensity exercise on a cycle ergometer. During the three cycling bouts subjects wore compression stockings during the test and recovery, just during the test, or not at all. It is unclear whether each subject performed the test under each condition or whether each subject was a part of only one experimental condition. Subjects that wore the graduated compression stockings had significantly lower lactate values at 15 minutes post-exercise in Experiment 1 and during recovery in Experiment 2. However, no significant differences were found in plasma volume shifts; the authors speculate that the lower lactate values may be due to the lactate being retained in the muscle.

Later studies began investigating other effects of compression garments on exercise, beyond the increased venous return and clearance of metabolites. Kraemer et al. (1996) noticed that the use of compressive garments was, at the time, most popular for athletes in power sports (basketball, track and field, volleyball). Thus, they decided to examine the influence of compression shorts on power production during maximal effort vertical jumping. Eighteen men and 18 women varsity volleyball players were tested on vertical jump performance in compression shorts of normal fit and undersized, and in loose fitting gym shorts (control). Subjects performed 10 consecutive maximal countermovement vertical jumps (one every three seconds) on a force plate. The compression shorts had no effect on maximal force or power of the highest jump. However, the mean force and power production over the series of jumps was significantly higher ($p<0.05$) for the normal fitting compression shorts than for the control. In men, the mean force and power production was also significantly higher in the undersized shorts than in the control. Conversely, subsequent research by Kraemer et al. (1998) found no significant differences in muscle fatigue between commercially available compression shorts and control conditions. Subjects performed three sets of 50 maximal isokinetic knee extensions ($180°\cdot s^{-1}$) and the maximal number of repetitions at 70% one-repetition-maximum using a squat exercise machine. Peak torque and total work performed were not affected by the compression garment.

Bernhardt and Anderson (2005) also found no significant differences in a number of variables when wearing compression shorts during standing, sprinting, and jumping activities. Subjects completed two randomized testing sessions, one wearing Coreshorts compression shorts and one while not wearing the shorts. Testing consisted of both performance and proprioceptive measures. Leg power, agility, speed, and aerobic endurance were not affected by the compression shorts. Active range of motion was the only measured variable significantly altered (decreased) by compression shorts ($p<0.05$). Responses to the subjective questions indicated that subjects did not find the shorts to hinder performance, with nearly all subjects (93.31%) saying the compression shorts were supportive. On the other hand, only 38.46% of subjects said they would wear the shorts during sporting activities. However, it is important to note that the subjects in this study were healthy college students; the subjective responses of competitive or elite athletes may be quite different.

Doan et al. (2003) found more promising results when they examined how custom-fit compression shorts affected athletic performance of 10 male and 10 female track athletes, specializing in sprints and jumps, on a nationally competitive university track team. The researchers sought to investigate possible mechanisms contributing to increased repetitive jump power (as described by Kraemer et al., 1996), including reduced muscle oscillation, improved proprioception, and increased resistance to fatigue. A number of interesting variables were found to be significantly affected by the compression shorts: hip flexion angle while sprinting was reduced, skin temperature increased higher and more rapidly, muscle oscillation was reduced, impact force was reduced, and countermovement vertical jump height increased (in contrast to previous studies). Manufacturers of compressive garments often make claims regarding muscle oscillation. For example, Speedo's FS-PRO supposedly "improves muscle efficiency through reduction of excess muscle vibration" (www.speedousa.com). The method for measuring muscle oscillation in this study was simply a 60 Hz video camera; the validity of this motion capture system to evaluate muscular oscillation is questionable.

In one of the few studies investigating lower leg compression and distance running, Ali et al. (2007) measured heart rate, ratings of perceived exertion, ratings of soreness, and performance during intermittent (shuttle run) and continuous (10 kilometer) overground running. The authors noted that 10 of the 14 participants ran faster in the 10k run with compression stockings; however their focus on that statement is unwarranted because no significance was actually found. Furthermore, subjects were supposedly paced by an investigator on a bicycle; thus, no differences in time *should* have been found. They did determine that wearing the compression stockings resulted in reduced delayed-onset muscle soreness after the continuous run ($p<0.05$); however, no other findings were significant.

More recently, researchers have examined the effect of compression stockings on running performance, this time using more objective performance measures (Kemmler et al. , 2009). Maximum running performance, as determined by time under load (TUL) (min), work (kJ), and aerobic capacity ($ml \cdot kg^{-1} \cdot min^{-1}$), was measured at the aerobic (AT) and anaerobic (AnT) thresholds in moderately trained men (n=21). The AT was defined as the minimum lactate under the load + 0.5 $mmol \cdot L^{-1}$; AnT was defined as minimum lactate + 1.5 $mmol \cdot L^{-1}$. TUL, total work, and maximum speed increased at both thresholds with compression treatment, as compared to the control. However, there were no differences in maximal or threshold values of oxygen consumption, heart rate, expiratory ventilation, blood lactate, and the respiratory exchange ratio between control and treatment conditions . When speculating on the mechanism underlying the improvement in performance (without an improvement in maximal or submaximal oxygen consumption), the authors suggest that the increased biomechanical support of the muscle and muscle-tendon unit may produce greater mechanical efficiency.

Research on compression garments has focused on physiological and performance measures, with inconsistent results. Metabolite clearance, proprioception, force production, thermoregulation, and subjective measures have been evaluated as mechanisms to improve performance with compression. A decrease in active range of motion, perhaps due to increased leg stiffness, has been noted; however, the effect of compression on biomechanical variables has not been thoroughly investigated.

Summary

From the previous literature it is clear that success in distance running depends in part on running economy. As Foster and Lucia (2007) concluded, since high level athletes already possess a high VO_{2max}, whether through training or talent, as well as the ability to perform at a high percentage of VO_{2max}, future improvements in running performance may depend on improved economy. The literature indicates that the potential for improving running economy exists; however, it is important that appropriate interventions and targeted variables are chosen. Research supports a strong relationship between running mechanics and economy; thus, one approach to improving running economy may be via altering running mechanics. Studies have shown that marked changes in biomechanics, and even running economy, can be made with specific gait manipulations during exercise. Lower leg compression sleeves, which have recently gained worldwide popularity among competitive athletes, could potentially evoke changes in biomechanics. Research on compression garments has focused on physiological and performance measures, with inconsistent results; however, the effect of compression on biomechanical variables has not been thoroughly investigated. In theory, compression could change stiffness and mechanics, thereby having an ergogenic effect. Preliminary observations by our laboratory have indicated that wearing lower leg compression sleeves reduces ground contact time in elite runners and may have an effect on other mechanical variables. These biomechanical characteristics are specifically associated with better running economy. By altering one or more of these mechanical variables with moderate lower leg compression, running economy, and ultimately performance, may be improved.

CHAPTER 3

EXPERIMENTAL PROCEDURES

The purpose of the study was to examine whether wearing moderate lower leg compression sleeves evokes changes in running economy due to alteration of gait mechanics. The conduct of the study included the following organizational steps: (a) selection of subjects; (b) experimental design; (c) instrumentation; (d) running economy testing; (e) gait measures, and (f) treatment of data.

Selection of Subjects

Subjects (N=16) were highly trained males, recruited primarily through Team Indiana Elite and the Indiana University men's cross country and track teams. Sixteen subjects were chosen based on calculations from preliminary observations in our laboratory (power=0.80), as well as previous studies measuring changes in running economy and gait mechanics. Male subjects have been used in the majority of investigations on running economy in highly-trained and elite distance runners, allowing appropriate submaximal speeds to be determined; however, the same cannot be said for elite female distance runners. The specialty racing events of these athletes included the 1500m, 3000m steeplechase, 5000m, and the 10000m. Primary inclusion criteria were an age between 18 and 30 years and a time of less than 16 minutes 30 seconds for a 5000 meter race within the past year. Subjects who had not raced a 5000m in the past year were deemed highly trained by 1500 meter or 10000 meter race times, or VO_{2max} measures obtained within the past year. Exclusion criteria included injury or illness that impaired normal training and racing within two weeks prior to the study. Subjects gave written informed consent before testing, and all protocols and procedures used in testing were approved by the Institutional Review Board of Indiana University.

Experimental Design

Subjects were required to complete a single experimental session lasting approximately 60 minutes. A one-time testing session was chosen to control for daily variance that may affect the potentially small changes being measured, as well as to minimize subject burden. Before any experimental measures were taken, subjects completed a survey regarding their training and race performances over the past six months, as well as their experiences and beliefs regarding lower leg compression sleeves. Measures of height (cm), mass (kg), and calf circumference (in) were recorded before beginning the testing session. Two separate running economy tests took place during the session. The sequence of running economy tests, with a treatment trial of compression sleeves (T) and a control trial without compression sleeves (C), were counterbalanced, with 10 minutes between trials. Gait variables were measured during the last 30 seconds of each four-minute stage of the running economy test. For both the T and C tests, subjects wore lightweight racing flats, wearing the same pair of flats during each test.

Instrumentation

1. Zensah Training and Muscle Recovery Leg Sleeves were worn by the subjects during the T testing session (Zensah, Miami, FL). The manufacturer recommendations for determining correct size based on calf circumference were used.
2. The following equipment was utilized in the running economy determinations:
    a. Motorized treadmill. The treadmill used in this study can be regulated with the Quinton Treadmill Control to speeds of 0-15 miles per hour and grades of 0-40 percent (Quinton, Bothell, WA).
    b. Digital Laser Tachometer (Model: DT-2234C, Kernco, El Paso, TX) for measuring treadmill speed.

c. Gas collection apparatus. This included (a) Hans Rudolph (Kansas City, MO) breathing valves, (b) Noseclips, (c) Pneumotach #3813 and Pneumotach Amplifier # 1110 (Hans Rudolph) (d) Flow probe, (e) CO_2 and O_2 sensors, analyzers and flow control (Ametek, Applied Electrochemistry), (f) Perma Pure desiccant membrane dryer (Model #DM -110-24, Perma Pure, LLC., Toms River, NJ), (g) Calibration gas (Airgas Inc.), and (h) Mixing chamber.

d. Stopwatch.

e. Weight and height measuring scales.

f. Dell computer with DasyLab software programming and an analog to digital converter board.

3. Gait variables were measured via wireless tri-axial 10g accelerometer devices (G-link, Microstrain, Williston, VT). Accelerometer raw data was processed via a computer program developed in-house.

Running Economy Testing

Prior to the running economy testing, each subject's mass was taken while standing on a portable digital scale in his running shorts (no shoes). Each subject's height was taken with a stadiometer while wearing running attire (no shoes). Subjects were asked to stand straight with feet together and weight evenly distributed. Each subject's head was placed in Frankfort horizontal while their arms hung freely by the sides of the trunk (Lohman, Roche, & Martorell, 1988).

Running economy was determined by measuring oxygen consumption at three constant submaximal speeds of 233, 268, and 300 $m \cdot min^{-1}$ on a motorized treadmill (Quinton, Bothell, WA). Treadmill speed was verified through the use of a laser tachometer (Model: DT-2234C) and revolutions per minute (RPM) vs. speed charts developed specifically for the length of the treadmill belt. Running economy was calculated from a) the VO_2 measured over the final 60s of each four minute stage at each speed, and b) the slope of line relating VO_2 vs. running speed.

Ventilatory and metabolic variables were continuously measured and monitored during exercise using a computer interfaced, open flow, indirect calorimetry system. Minute ventilation was determined using a Hans Rudolph pneumotach (#3813) and amplifier (#1110) on the inspired side. Subjects breathed through a low resistance, two-way valve (#2700, Hans Rudolph), and a 5-liter mixing chamber was used for the collection of expired gases. Fractional concentrations of O_2 and CO_2 were determined from dried expired gas, sampled at a rate of 300 $ml \cdot min^{-1}$, using separate O_2 and CO_2 gas analyzers (AEI Technologies, Pittsburg, PA). Analyzers were calibrated prior to each test using commercially available gas mixtures within the physiological range, whose fractional contents were verified by mass spectroscopy. V_E, VO_2, and VCO_2 were averaged over each minute of exercise, with V_E corrected to BTPS and VO_2 and VCO_2 corrected to STPD. The above variables, as well as F_EO_2 as F_ECO_2, were continuously measured and monitored with a data acquisition control system (DASYLab 10.0, National Instruments, Norton, MA) sampling at 50 Hz.

Gait Measures

To measure variables related to running gait, accelerometric data was gathered during the last 30 seconds of each four-minute stage of the running economy test.

Separate wireless tri-axial 10g accelerometer devices (G-link, Microstrain, Williston, VT) were attached to the top of each foot, utilizing plastic ties to attach the device to the shoelaces. The accelerometers sampled each axis at a rate of 1024 Hz, with data from each 30s stage being stored in separate files. Accelerometer data was analyzed using a custom in-house program, following a procedure similar to one described by Weyand and colleagues (2001). Briefly, the waveform output from the Y-axis and Z-axis of the accelerometer was used to identify the precise times of the foot contacting the ground and the foot toeing-off from the ground (i.e. breaking contact). To verify the ground contact and toe-off markers, the accelerometric output has been compared to simultaneously collected high speed video (Elixim EX-F1, Casio, Tokyo) sampling at either 300 frames·s^{-1} (n =3) or 600 frames·s^{-1} (n = 1), collected on 4 male subjects at 9 running speeds. The accelerometer and video measures were highly correlated (R^2 = 0.99), with no single pair of measurements differing by more than 0.003 seconds. An example of the accelerometer output waveform used for ground contact and toe-off identification is shown in a representative trace in Figure 2 (Weyand et al., 2001).

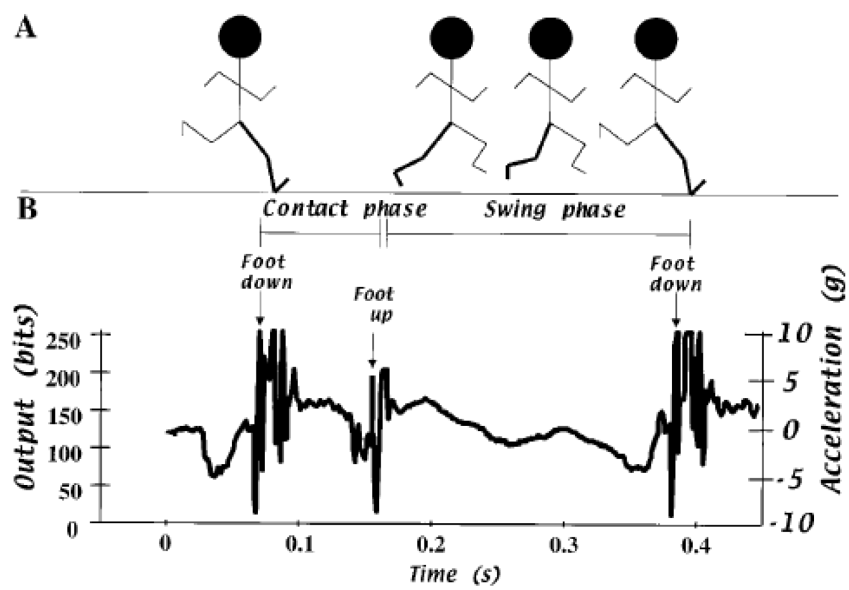


Figure 2. Foot ground contacts and swing periods of a representative running stride (A) and simultaneous waveform output from an accelerometer (B) (adapted from Weyand et al., 2001).

From this accelerometric output, we were able to quantify: a) foot ground contact time (t_c), defined as the time (in s) from when the foot contacts the ground to when the foot toes-off (i.e. breaks contact with the ground), b) swing time (t_{sw}), defined as the time (in s) from toe-off to ground contact of consecutive footfalls of the same foot, c) stride frequency, defined as the number of ground contact events (i.e. steps taken) per minute, and d) stride length, defined as the length (in m) from toe-off to ground contact in successive steps, calculated from stride frequency and treadmill speed. Values of ground contact time, swing time, stride length, and stride frequency were determined and calculated from the average of accelerometric values obtained from a minimum of 20 consecutive steps.

Before each treatment trial, an estimate of the pressure exerted by the compression sleeve on the lower leg was obtained using a flexible piezoelectric force sensor (FlexiForce sensor Model #A201-1, Tekscan, Inc., Boston, MA). The sensor was incorporated into a force-to-voltage circuit, which was calibrated to convert the voltage output from the data acquisition control system (DASYLab 10.0, National Instruments, Norton, MA) to units of pressure. The largest part of the subject's calf was marked, and the sensor was placed at that point, between the skin and the compression sleeve. Raw voltage output was collected for approximately one second, two to three times, with the sensor removed in between each collection.

Vertical leg stiffness estimates were calculated post hoc, as described by Hobara et al. (2009), utilizing measures of body mass, height, flight time and ground contact time.

Treatment of data

Descriptive statistics were used to describe the characteristics of the group, and Pearson correlations were used to quantify relationships between mechanical and metabolic variables. Paired t-tests were utilized to assess differences in the outcome measures of ground contact time, swing time, stride length, stride frequency, leg stiffness and submaximal oxygen consumption at the different running speeds during T and C testing sessions. Statistical significance was set at $p < 0.05$.

CHAPTER 4

RESULTS

The current investigation sought to determine whether or not wearing lower leg compression sleeves evokes changes in running economy and running mechanics. Topics discussed in this chapter include results regarding the following: (a) subject characteristics, (b) running economy, and (c) running mechanics.

Subject Characteristics

Sixteen highly trained male distance runners participated in the current study. All subjects were determined fit to participate in the study, as assessed by the Modified Physical Activity Readiness Questionnaire (PAR-Q). Subject anthropometric data are displayed in Table 1. Subjects were all classified as highly trained, based on a criterion measure of a 5000 meter race time of 16 minutes 30 seconds or less within the past year. Subjects who had not raced a 5000m in the past year were deemed highly trained by equivalent performance times in the 1500 or 10000 meters (McMillan, 2006), or VO_{2max} measures obtained within the past year.

Age (yrs)	22.4 ± 3.0
Height (cm)	180.6 ± 4.6
Weight (kg)	66.4 ± 5.2
BMI	20.4 ± 1.4
Calf circumference (in)	13.87 ± 0.61

Table 1. Subject characteristics. Mean ± SD.

Subjects reported running an average of 6.5 ± 0.9 days·week^{-1} and 62.2 ± 19.7 miles·week^{-1} during the six months prior to the study. Data describing the subjects' race performances over the past year are displayed in Table 2.

Event	Average Time (mm:ss)	Range
1500m (n=8)	3:56.2 ± 12.6	3:39 – 4:15
5000m (n=12)	14:47.2 ± 62.2	13:41 – 16:30
10000m (n=4)	29:22 ± 35.72	28:52 – 30:10

Table 2. Reported personal best race performances during the one year prior to the study. Mean ± SD and range.

All subjects (n=16) were familiar with/had heard about lower leg compression sleeves and had seen runners wearing lower leg compression sleeves. Over half of the subjects (n=10) personally knew someone who had worn lower leg compression sleeves, and five subjects had worn lower leg compression sleeves themselves. Some subjects believed lower leg compression aided runners in training (n=5) and in competitive performance (n=6), and the majority reported a belief in compression aiding recovery (n=10).

Compression sleeve beliefs did not have any impact on any of the other reported measures, gait variables, or submaximal oxygen consumption values ($p > 0.05$).

Running Economy

There were no significant differences in submaximal oxygen consumption (VO_2) between control and treatment trials at any of the speeds (Fig. 3; *p* values = 0.701 – 1.00). At 233 m·min^{-1}, mean oxygen consumption was 46.7 ± 1.6 ml·kg^{-1}·min^{-1} (C) and 46.5 ± 1.5 ml·kg^{-1}·min^{-1} (T). At 268 and 300 m·min^{-1}, submaximal VO_2 was 54.0 ± 1.6 ml·kg^{-1}·min^{-1} (C) and 54.0 ± 1.7 ml·kg^{-1}·min^{-1} (T), and 62.1 ± 1.7 ml·kg^{-1}·min^{-1} (C) and 62.2 ± 1.8 ml·kg^{-1}·min^{-1} (T), respectively.

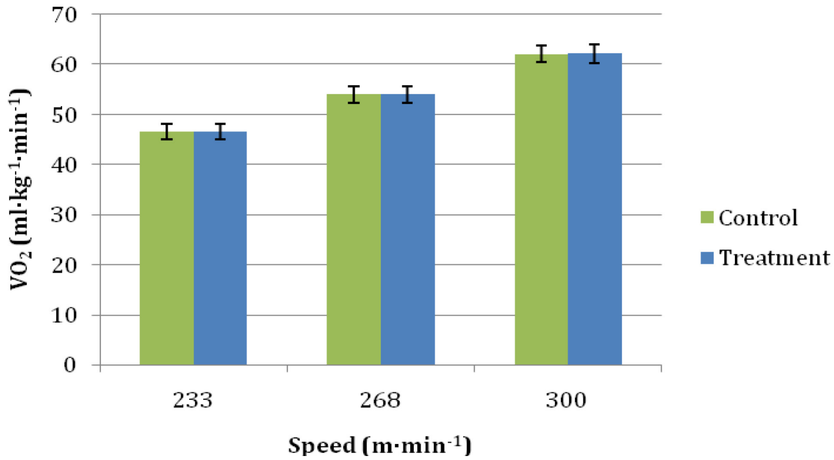


Figure 3. Submaximal oxygen consumption during control and treatment conditions. Displayed are means ± SE.

Additionally, there was no significant difference (p = 0.535) in the slope of the lines relating submaximal VO_2 and running speed between the two experimental conditions (Fig. 4).

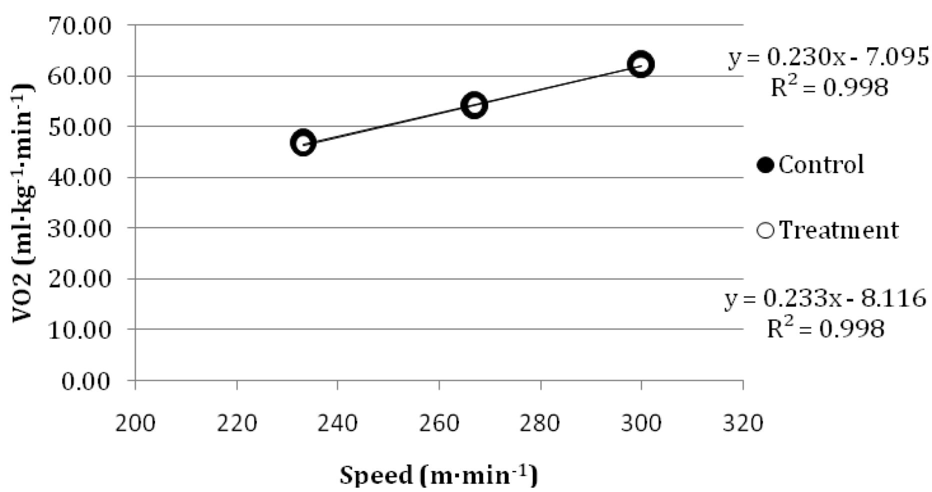


Figure 4. Running economy slopes during control and treatment conditions.

In both the control and treatment conditions, resting VO_2 was significantly correlated with oxygen consumption at 233 and 268 $m \cdot min^{-1}$ and resting heart rate (HR) (r = 0.68, 0.57, and 0.66, respectively; $p < 0.05$). Submaximal VO_2 at each speed was significantly positively correlated with oxygen consumption at all other speeds and with HR at the corresponding speed. Submaximal VO_2 at each speed was also correlated with 1500m and 5000m race times (r = 0.59 – 0.92; $p < 0.05$).

Running Mechanics

There were no significant differences ($p > 0.05$) in ground contact time (t_c), swing time (t_{sw}), stride time (t_{st}), stride frequency (SF), and stride length (SL) between control and treatment conditions at any of the running speeds (Table 3).

Speed ($m \cdot min^{-1}$)	**Condition**	**Gait variable**				
		Ground contact time (s)	**Swing time (s)**	**Stride time (s)**	**Stride frequency ($steps \cdot min^{-1}$)**	**Stride length (m)**
233	C	.204 ± .003	.507 ± .010	.709 ± .009	169.85 ± 2.26	1.38 ± .02
	T	.205 ± .003	.506 ± .009	.709 ± .009	169.60 ± 2.11	1.38 ± .02
268	C	.188 ± .003	.503 ± .010	.690 ± .009	174.39 ± 2.21	1.53 ± .02
	T	.189 ± .003	.500 ± .009	.689 ± .008	174.61 ± 2.10	1.53 ± .02
300	C	.175 ± .002	.495 ± .008	.670 ± .008	179.39 ± 2.21	1.68 ± .02
	T	.175 ± .002	.495 ± .009	.669 ± .008	179.65 ± 2.18	1.67 ± .02

Table 3. Gait variables during control (C) and treatment (T) conditions (mean ± SE).

Gait variability, as defined by the standard deviation of a given gait variable for an individual during approximately 30 seconds of running, was not significantly different from control to treatment conditions at any of the speeds ($p > 0.05$) (Table 4). However, variability in stride time and stride length tended to decrease with compression treatment significance at the speed of 300 m·min^{-1} (p = 0.073 for each); the effect size for each was 0.54 (1 – β = 0.81), with an estimated sample size of n = 29 necessary to see significance.

Speed (m·min^{-1})	**Condition**	**Gait variability (SD)**				
		Ground contact time	**Swing time**	**Stride time**	**Stride frequency**	**Stride length**
233	C	.0059 ± .0012	.0096 ± .0013	.0067 ± .0004	1.62 ± 0.12	.013 ± .001
	T	.0066 ± .0014	.0088 ± .0012	.0065 ± .0007	1.57 ± .17	.013 ± .001
268	C	.0055 ± . 0010	.0086 ± .0012	.0067 ± .0009	1.71 ± .22	.015 ± .002
	T	.0052 ± .0011	.0080 ± .0009	.0068 ± .0009	1.72 ± .21	.015 ± .002
300	C	.0054 ± .0008	.0086 ± .0010	.0072 ± .0008	1.93 ± .21	.018 ± .002
	T	.0051 ± .0014	.0082 ± .0015	.0067 ± .0007	1.81 ± .19	.017 ± .002

Table 4. Variability (SD) in measured gait variables during control (C) and treatment (T) conditions (mean ± SE).

Ground contact time was inversely correlated with submaximal oxygen consumption, as described by Kram and Taylor (1990) and Weyand et al. (2001). Figure 5 shows the relationship between the inverse of ground contact time ($1/t_c$) and oxygen consumption for each individual during the three speeds of the control condition. The average coefficient of determination (R^2) was 0.96.

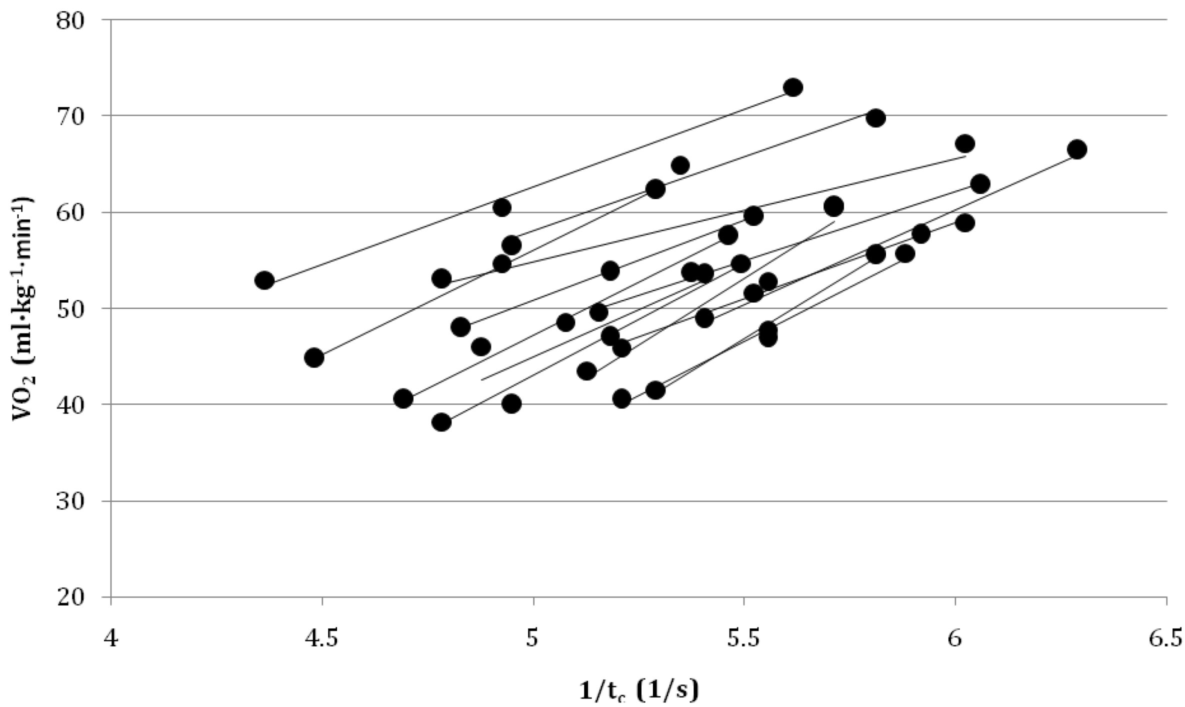


Figure 5. Mass-specific rates of oxygen consumption (VO_2) increase linearly with inverse ground contact time ($1/t_c$).

Differences between "positive" and "negative" responders

Although there was no significant group difference in submaximal VO_2 between control and compression treatment, there was a large inter-individual variability in response to compression. Four subjects demonstrated an average of >1% reduction in submaximal VO_2 with compression (Equation 2); likewise, four subjects exhibited an average of >1% increase in submaximal VO_2 with compression treatment.

$$\Delta VO_2 (\%) = (VO_{2treatment} - VO_{2control}) / VO_{2control} * 100 \qquad [2]$$

Because the magnitude of reduction/increase in submaximal VO_2 in these subjects is large enough to have potential performance implications (Di Prampero et al., 1993; Fallowfield & Wilkinson, 1995; Gore et al., 2001), a post hoc analysis was completed, comparing the measured variables of the four subjects with the most positive metabolic responses to compression to the four subjects with the most negative responses. The subjects who showed the >1% reduction in VO_2 response to compression were considered "positive responders" (P), and the subjects with >1% increase in VO_2 were deemed "negative responders" (N) (Table 5).

Subject	ΔVO_2 (%)			
	233 m·min^{-1}	268 m·min^{-1}	300 m·min^{-1}	Average
1	-3.8	-0.8	3.0	-0.5
2	0.1	4.0	-0.8	1.1
4	-0.7	0.5	-3.3	-1.2
5	-3.0	-0.1	2.3	-0.3
6	1.0	-2.1	4.0	1.0
7	-1.8	-1.0	-2.6	-1.8
8	-1.2	0.6	2.2	0.5
9	-4.3	1.4	1.4	-0.5
10	0.5	-4.7	-3.3	-2.5
11	3.5	2.5	0.7	2.2
12	-0.8	0.6	-1.3	-0.5
13	-0.3	0.0	2.6	0.8
14	-3.1	-6.2	-5.0	-4.8
15	7.0	4.9	3.3	5.1
16	3.0	0.5	-1.2	0.8

Table 5. Individual changes in VO_2 from control to treatment conditions. N are shaded in dark gray; P in light gray.

The treatment effect (group * treatment) was significantly different between positive and negative responders at a running speed of at 300 m·min^{-1} (p = 0.006) and nearing significance at speeds of 233 m·min^{-1} (p = 0.052) and 268 m·min^{-1} (p = 0.068). There was no significant difference in submaximal VO_2 at any speed between P and N (p = 0.469 – 0.868).

There was no significant difference in the treatment effect between groups for any of the measured gait variables. However, the group by treatment interaction was nearing significance (p = 0.061) for stride frequency at a running speed of 300 m·min^{-1}; negative responders tended to exhibit a greater increase in SF with compression treatment than positive responders. Additionally, the response of stride length to compression treatment was nearing significance (p = 0.072) between groups; positive responders tended to exhibit an increase, while negative responders showed a decrease, in SL at 300 m·min^{-1}.

Positive responders showed less variability in stride time, SF, and SL than negative responders while wearing compressions sleeves at the slowest speed (p = 0.066, 0.041, 0.066, respectively) (Fig. 6).

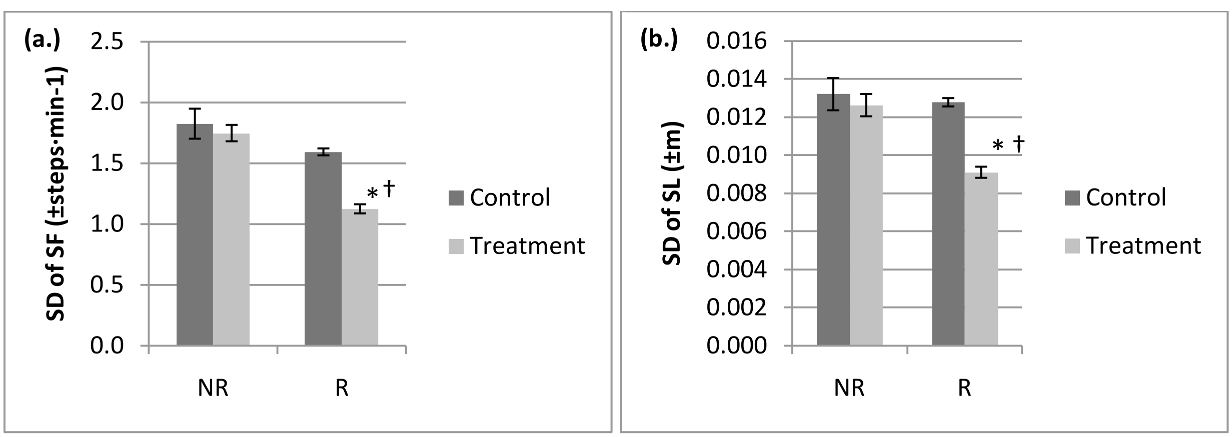


Figure 6. Variability in (a) stride frequency and (b) stride length of "positive" and "negative" responders running at 233 m·s^{-1} during control and treatment conditions. *significant difference between control and treatment, $p < 0.05$. †significant difference between N and P, $p < 0.05$.

Additional tables and raw data are found in Appendix A.

CHAPTER 5

DISCUSSION

The purpose of this study was to examine whether wearing moderate lower leg compression sleeves evokes changes in running economy due to altered gait mechanics. Previous research has demonstrated that running mechanics and running economy are tightly linked; thus, altering one or more gait variable(s) while running may subsequently change running economy. In theory, compression could change muscle stiffness and joint mechanics, thereby having an ergogenic effect. The current investigation demonstrated that lower leg compression does not significantly change running mechanics, nor does it influence mean oxygen consumption while running at submaximal speeds. This conclusion is supported by the lack of significant differences in all gait variables and VO_2 measures between the control (no compression) and treatment (compression) conditions.

To the author's knowledge, only three other studies have investigated the effect of leg compression on markers of running economy, and no other study has examined the impact of compression on the gait variables of ground contact time, swing time, stride length, or stride frequency. The results of the present study are discussed with regards to the previous literature.

Subjective Measures

The pre-testing subjective questionnaire was given to determine the subjects' experiences with and opinions of lower leg compression sleeves. Though there were no significant correlations between survey responses and any measured variable of the group, an interesting observation was made: the two subjects with the most "positive" metabolic response to compression treatment (i.e., largest decrease in oxygen consumption at a given submaximal speed) were the only two subjects who had worn compression sleeves themselves AND believed compression aided in each of the following: (a) training, (b) racing, and (c) recovery. Perhaps, as may have been the case in the study by Kemmler et al.

(2009), where "performance" improved, despite no change in running economy or maximal oxygen consumption, the positive impact of compression sleeves seen in some athletes may have a psychological basis.

Running Economy

It was hypothesized that wearing lower leg compression would significantly alter running economy. The data from the current investigation does not support this hypothesis. Submaximal oxygen consumption did not change at any running speed from the control (C) to treatment (T) condition. Effect sizes (η_p^2) for the change in VO_2 with compression were minuscule, ranging from 0.00-0.013 ($1 - \beta = 0.05$-0.065) at the different speeds. Similar to the data in the study, Kemmler et al. (2009) saw no change in oxygen consumption at the aerobic and anaerobic thresholds of moderately trained runners (n=21) when wearing compressive stockings as compared to the control, despite finding significantly improved running performance with compression. Conversely, pilot data from Bakken, Borgen, Willis, and Heil (2009, abstract form) demonstrated evidence for compression having a positive influence on running economy in highly trained cross-country skiers; however, the study had only five subjects, which may have allowed the performance of a few individuals to have a large effect on the data, rendering the data less representative of the population. Additionally, the marker of running economy used in the investigation (ΔVO_2 from the first time interval VO_2 value) was only significantly different with compression at one of the six time intervals over 60 minutes of running. An earlier study by Bringard, Perrey, and Belluye (2006) showed mixed results, with a significantly lower energy cost while wearing compression tights at one of four submaximal speeds (12 $km \cdot hr^{-1}$) in trained runners (n=6). Results from previous research have been inconsistent due to differences in sample size, compression garment, training level (e.g., moderate vs. highly trained), and training type (e.g. runners versus cross-country skiers). The current study contributes to the collective body of knowledge as highly trained runners and a moderate sample size were utilized.

When looking at the slope of the line relating speed and oxygen consumption, there was also no significant difference between control and treatment trials. Slopes of the lines were comparable to previous literature investigating running economy of elite distance runners. Daniels and Daniels (1992) measured running economy of elite male and female runners, the majority of whom had qualified for the Olympic Trials. The slope of the running economy line for the elite males was 0.240; for the highly-trained runners in the present study, the slopes were 0.230 and 0.233 (C and T, respectively).

Running Mechanics

It was hypothesized that lower leg compression would significantly alter foot ground contact time, swing time, stride length, and stride frequency during treadmill running. The data from the current investigation does not support this hypothesis. There was no significant difference in any gait variable from the control to treatment condition at any running speed; effect sizes (η_p^2) for the gait variables ranged from 0.005 to 0.151 ($1 - \beta$ = 0.056-0.270). No previous research has investigated the effect of compression on the mechanical variables measured in the present study. However, a few studies have collected other biomechanical data regarding compression; overall, results from previous investigations suggest lower body compression garments influence lower body mechanics by limiting the range of motion (ROM) in the lower limbs (Doan et al., 2003; Bernhardt & Anderson, 2005; Bakken et al., 2009). Decreased ROM is associated with increased stiffness (McNair & Stanley, 1996; Gajdosik, Vander Linden, & Williams, 1999), which, in turn, impacts gait variables such as those measured in the present study (McMahon et al., 1987; McMahon & Cheng, 1990). Thus, the previous literature would suggest lower body compression may impact gait mechanics. Bringard et al. (2006) and Kemmler et al. (2009) seem to support this hypothesis in proposing that compression treatment may act through increased biomechanical support of the muscle-tendon unit, ultimately resulting in greater mechanical efficiency. The inability of compression to exert an effect on running mechanics in the current study could be due to a number of factors, including the targeted gait variables, the level and/or location of compression exerted by the Zensah sleeve, the sensitivity of the measurement device, and the subject population. The potential impact of these factors will be discussed with regard to present study.

Though the targeted gait variables had not been investigated in previous research, it is unlikely that the lack of significance found in the present study was the result of poorly chosen measures. Ground contact time, stride length, and stride frequency have all been shown to relate to the energy cost of running; thus a study investigating both mechanics and economy should examine these variables. As mentioned previously, decreased ROM is associated with increased stiffness, which, in turn, impacts gait variables, including ground contact time, stride length, and stride frequency. Thus, the previous literature would suggest lower body compression could impact the gait mechanics measured in the present study.

During submaximal running, the majority of stored energy comes from the muscles and tendons supporting the ankle and knee; for the lower leg, this refers specifically to the triceps surae (gastrocnemius and soleus muscles) and the Achilles tendon (Alexander, 1987; Arampatzis, De Monte, Karamanidis, Morey-Klapsing, Stafilidis, & Bruggemann, 2006). The lower band of the compression sleeve used in the present study sat immediately superior to the lateral malleolus; thus, though it covered most of the triceps surae and a portion of the tendon, the compression did not cover the entire Achilles tendon, nor did it surround the ankle joint, itself. In the previous investigations finding decreased ROM, the garment completely covered the (hip) joint about which ROM was reduced. Furthermore, though the estimates of leg stiffness obtained in the current study were comparable to estimates reported by Hobara et al. (2009), there were no significant differences in these estimates between the control and treatment conditions. Lastly, the precise level of compression exerted by the sleeves on the calf in the current study is unknown. The measurement tool utilized to obtain compression values did not provide consistent output. The grade of compression of the Zensah sleeves may be significantly different than that of garments used in previous studies.

The in-house program developed to analyze the wireless accelerometer output can identify the time that the foot makes contact with and toes-off from the ground within one millisecond. When compared to simultaneously collected high speed video, the accelerometer and video measures were highly correlated ($R^2 = 0.99$), and no single pair of measurements differed by more than three milliseconds. However, the average absolute change in ground contact time from control to treatment for the present study was just under one millisecond (mean = 0.00098). Thus, the measurement device may not have been sensitive enough to identify significant differences between treatment conditions. Nonetheless, the relevancy of the potential changes in running mechanics with compression is questionable if the differences between conditions were too minuscule to be detected by a fast-sampling, industrial grade accelerometer.

The subjects in the present study were highly trained distance runners, whereas previous studies have utilized less fit subjects and athletes specializing in other events (i.e., sprinters, skiers). Attempts to alter running mechanics have been most successful in clinical populations and in novice or moderately trained runners (Messier and Cirillo, 1989; Crowell et al., 2005; Davis, 2008). It appears that altering habitual gait patterns in highly-trained athletes is more difficult. Morgan and Martin (1986) demonstrated that highly-trained racewalkers consistently select the most economically optimal locomotion style; deviating from the preferred gait mechanics results in significant decrements in walking economy. Furthermore, runners are able to maintain similar gait movement patterns, despite external interference, such as changes in surface properties. For example, runners adjust leg stiffness, while maintaining the path of the center of mass, to make a smooth transition between surfaces of varying stability and stiffness (Ferris et al., 1998; Ferris et al., 1999). Adjusting leg stiffness allows runners to maintain similar running mechanics and stability on different surfaces. Therefore, our subject cohort, being highly-trained distance runners, may have been able to continue to select the most economical running pattern despite the "interference" of lower leg compression.

Economy-Gait Relationship

Ground contact time was inversely correlated with mass-specific rate of oxygen uptake during submaximal running, as described by Kram and Taylor (1990) and Weyand et al. (2001). The former reported an inverse relationship between rate of energy used for running and time the foot applies contact to the ground in a number of different mammals. Weyand et al. (2001) later showed how this relationship in humans, taken in conjunction with heart rates, could be used to estimate maximal aerobic power. The variability in submaximal oxygen consumption was almost entirely accounted for by $1/t_c$ in individuals (98%); however, considerable between-subject variation caused the proportion of variance in relative VO_2 to be less among the entire group (61%). In the current study, $1/t_c$ accounted for an average of 96% ($R^2 = 0.96$) of within-subject variance in relative VO_2, but accounted for only 32% ($R^2 = 0.32$) of variance in VO_2 among the group. The subjects in the present investigation were, overall, a more homogenous and aerobically fit group than those in the study by Weyand et al., which could account for the smaller coefficient of determination of the group. Similar relationships between stride frequency and stride length with relative VO_2 were observed.

Positive vs. Negative Responders

Significant changes in the economy of highly trained athletes have been seen as low as 1% (Gore et al., 2001). Although the group mean metabolic response to compression was not different from the control condition, four subjects displayed a >1% reduction in submaximal VO_2 with compression, and four subjects showed a >1% increase in VO_2 during treatment. Because running economy is so tightly linked to running performance, a change of 1% could have important performance implications. In a post hoc analysis, an examination was completed to see if there were any distinguishing characteristics which explained these individual responses to compression. Though the method of grouping subjects could be considered arbitrary, it was the author's intent to determine where potential differences in metabolic and mechanical response to compression between individuals may lie, and to use this information in future investigations (e.g., by screening potential subjects beforehand). The subjects (n=4) who showed the most positive response to compression (i.e., greatest negative ΔVO_2) were considered "positive responders" (P), and the subjects (n=4) with the most negative response (greatest positive ΔVO_2) were deemed "negative responders" (N). When subjects were grouped in this manner, several significant differences between groups were found. Besides the obvious difference in metabolic response to compression treatment, the positive and negative responders exhibited significant differences in gait variability, as well as in the direction of change of some gait variables during T. The stride time, stride length, and stride frequency variability measures were significantly different between groups during the treatment condition at the slowest speed, 233 $m \cdot min^{-1}$. Variability in intraindividual stride length has been shown to decrease with increases in running speed (Jordan, Challis, & Newell, 2005), thus it is reasonable that we did not see significant differences in gait variability between groups at the faster speeds. Decreases in gait variability could contribute to the decrease in submaximal VO_2 with compression treatment seen in the positive responders. However, the underlying cause as to why compression would affect the gait variability of some subjects and not others is unknown.

The significant differences between groups in the degree/direction of change in stride length and stride frequency may also have had an impact on running economy changes with compression. The negative responders decreased stride length and increased stride frequency during T at the fastest speed; whereas, the positive responders had little to no change in SL and SF. As mentioned previously, highly trained athletes typically select the most optimal gait patterns, and deviations from the preferred movement result in increases in oxygen cost. If the control condition represents a preferred movement pattern, it appears that the treatment caused negative responders to deviate slightly from their optimal running mechanics for a given speed. The performance implications for changes in oxygen cost are important for the highly trained runner. In the current study, the average percent change in submaximal VO_2 with compression treatment for the responders was -2.6%; non-responders' average change was +2.3%. Previous investigations have found that a 5% improvement in running economy induce an approximately 3.8% improvement in distance running performance, and a 10% improvement in RE results in approximately 7% improvement in 3000 meter race performance (Di Prampero et al., 1993; Fallowfield & Wilkinson, 1995). The values from the previous two studies indicate a nearly linear relationship between the two variables; thus, assuming linearity, a 2.6% decrease in submaximal oxygen consumption could result in an approximately 2.0% improvement in performance. For the average 5000 meter race performance of subjects in this study (14:47), this would be a 17.7 second drop in 5000m race time. At the 2009 NCAA Men's Outdoor Track & Field Championships, 17 seconds separated the 13th place finisher from the 5000m national champion.

There was no significant difference in anthropometric data between groups, but the difference in calf circumference was nearing significance ($p = 0.063$, $\eta_p^2 = 1.36$), with positive responders tending to have smaller calf sizes. A power analysis showed that to see significance, ten subjects would be needed in each group ($1 - \beta = 0.82$). Lastly, three of the four positive responders reported a belief in lower leg compression sleeves aiding in race performance; whereas only one of four negative responders shared the same belief. This lends further evidence to a potential placebo effect with compression treatment.

Conclusion

This study has demonstrated that wearing lower leg compression sleeves does not significantly alter running mechanics or economy in highly trained male distance runners running at submaximal speeds. However, while there is no group difference with the sleeves, the individual response to wearing lower leg compression varies greatly, and future research should examine underlying differences between "positive" and "negative" responders to leg compression.

Recommendations for Future Research

Future research must first establish whether or not there are significant and relevant improvements in endurance exercise performance with lower leg compression. To the author's knowledge, there is no evidence to verify compression garments as ergogenic aids. Rather, many studies have been developed to assess *how* compression could improve performance, working under the assumption that it actually does. A large-scale, perhaps multi-institutional, study should be carried out to determine whether or not wearing lower leg compression sleeves has a positive, measureable impact on distance running race performance.

Additionally, any future investigations of compression garments should utilize a precise measurement tool to determine the pressure exerted by the compression garment on the body. Manufacturers of compression sleeves do not specify the level of compression that the garments provide, beyond vague descriptive terms. The measurement tool utilized in the current study did not provide consistent voltage output values and may not be an appropriate instrument for measuring pressure between two flexible surfaces.

The current investigation did not obtain VO_{2max} measures of the subjects. Since the largely homogenous group included only highly-trained distance runners, it is likely that maximal oxygen consumption values would be similar; however, the ability to report submaximal VO_2 values as a percent of maximum could potentially elucidate differences between groups, while certainly improving the overall depth of the study. Lastly, the effect of compression may become significant when looking at a more inclusive subject cohort, including less highly trained or untrained subjects. The metabolic and mechanical characteristics of highly trained athletes are more ingrained than those of their less trained counterparts; thus, the impact of compression could vary between subjects of different skill levels.

REFERENCES

Agu, O., Baker, D. & Seifalian, A.M. (2004). Effect of graduated compression stockings on limb oxygenation and venous function during exercise in patients with venous insufficiency. *Vascular*, 12(1), 69-76.

Agu, O., Hamilton, G. & Baker, D. (1999). Graduated compression stockings in the prevention of venous thromboembolism. *British Journal of Surgery*, 86, 992-1004.

Alexander, M. (1987). The spring in your step. *New Scientist*, 4, 41.

Ali, A., Caine, M.P. & Snow, B.G. (2007). Graduated compression stockings: Physiological and perceptual responses during and after exercise. *Journal of Sports Sciences*, 25(4), 413-420.

Anderson, T. (1996). Biomechanics and running economy. *Sports Medicine*, 22(2), 76-89.

Arampatzis, A., De Monte, G., Karamanidis, K., Morey-Klapsing, G., Stafilidis, S., & Bruggemann, G. (2006). Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. *The Journal of Experimental Biology*, 209, 3345-3357.

Bailey, D., Davies, B., Romer, L., Castell, L., Newsholme, E. & Gandy, G. (1998). Implications of moderate altitude training for sea-level endurance in elite distance runners . *European Journal of Applied Physiology and Occupational Physiology*, 78(4), 360-368.

Bakken, B., Borgen, K., Willis, S., & Heil, D. The influence of lower-body compression tights on markers of economy during steady-state running (Abstract). Presented at the 2009 Northwest American College of Sports Medicine conference.

Beneke, R. & Hutler, M. (2005). The effect of training on running economy and performance in recreational athletes. *Medicine and Science in Sports and Exercise*, 37(10), 1794-1799.

Bernhardt, T. & Anderson, G.S. (2005). Influence of moderate prophylactic compression on sport performance. *Journal of Strength and Conditioning Research*, 19(2), 292-297.

Berry, M.J. & McMurray, R.G. (1987). Effects of graduated compression stockings on blood lactate following an exhaustive bout of exercise. *American Journal of Physical Medicine*, 61(3), 121-132.

Bringard, A., Perrey, S., & Belluye, N. (2006). Aerobic energy cost and sensation responses during submaximal running exercise - Positive effects of wearing compression tights. *International Journal of Sports Medicine*, 27, 373-378.

Bushnell, T. & Hunter, I. (2007). Differences in technique between sprinters and distance runners at equal and maximal speeds. *Sports Biomechanics*, 6(3), 261-268.

Butler, R., Crowell III, H., & Davis, I. (2003). Lower extremity stiffness: implications for performance and injury. *Clinical Biomechanics*, 18, 511-517.

Caird, S., McKenzie, A., & Sleivert, G. (1999). Biofeedback and relaxation techniques improve running economy in sub-elite long distance runners. *Medicine and Science in Sports and Exercise*, 31(5), 717-722.

Cavagna, G.A., Saibene, F.P. & Margaria, R. (1964). Mechanical work in running. *Journal of Applied Physiology*, 19(2), 249-256.

Cavanagh, P. & Kram, R. (1985). The efficiency of human movement – a statement of the problem. *Medicine and Science in Sports and Exercise*, 17(3), 304-308.

Cavanagh, P., Pollock, M., & Landa, J. (1977). A biomechanical comparison of elite and good distance runners. *Annals New York Academy of Sciences*.

Conley & Krahenbuhl. (1980). Running economy and distance running performance of highly trained athletes. *Medicine and Science in Sports and Exercise,* 12(5), 357-360.

Costill, D.L., Thomason, H., & Roberts, E. (1973). Fractional utilization of the aerobic capacity during distance running. *Medicine and Science in Sports and Exercise,* 5(4), 248-252.

Crowell, H., Milner, C., Davis, I., & Hamill, J. (2005). Short-term Retention of Gait Changes After Real-time Feedback To Reduce Tibial Shock. *Medicine and Science in Sports and Exercise*, 37(5), S346.

Dalleau, G., Belli, A., Bourdin, M. & Lacour, J.R. (1998). The spring-mass model and the energy cost of treadmill running. *European Journal of Applied Physiology*, 77, 257-263.

Daniels, J. & Daniels, N. (1992). Running economy of elite male and elite female runners. *Medicine and Science in Sports and Exercise*, 24(4), 483-489.

Davis, I. (2008). *The Use of Real-Time Feedback to Alter Movement Patterns*. ACSM, Indianapolis, IN.

Di Prampero, P.E., Capelli, C., Pagliaro, P., Antonutto, G., Girardis, M., Zamparo, P. & Soule, R.G. (1993). Energetics of best performances in middle-distance running. *Journal of Applied Physiology*, 74(5), 2318-2324.

Doan, B.K., Kwon, Y.H., Newton, R.U., Shim, J., Popper, E.M., Rogers, R.A., Bolt, L.R., Robertson, M. & Kraemer, W.J. (2003). Evaluation of a lower-body compression garment. *Journal of Sports Sciences*, 21(8), 601-610.

Ergogenic aid. (2002). *Merriam-Webster's Medical Dictionary.* Retrieved January 2009 from http://dictionary.reference.com/browse/ergogenic

Fallowfield, J. &Wilkinson, D. *Improving Sports Performance in Middle and Long Distance Running: A Scientific Approach to Race Preparation.* Wiley and Sons: New York. 1995, P 35.

Ferris, D., Liang, K. & Farley, C. (1999). Runners adjust leg stiffness for their first step on a new running surface. *Journal of Biomechanics*, 32, 787-794.

Ferris, D., Louie, M. & Farley, C. (1998). Running in the real world: adjusting leg stiffness for different surfaces. *Proceedings of the Royal Society B*, 265, 989-994.

Foster, C. & Lucia, A. (2007). Running economy: The forgotten factor in elite performance. *Sports Medicine*, 37(4-5), 316-319.

Friel, J. (2007, October 28). Can your socks make you faster? Message posted to http://www.trainingbible.com/joesblog/

Gajdosik, R., Vander Linden, D., & Williams, A. (1999). Influence of age on length and passive elastic stiffness characteristics of the calf muscle-tendon unit of women. *Physical Therapy*, 79(9), 827-838.

Gleim, G., Stachenfeld, N., & Nicholas, J. (1990). The influence of flexibility on the economy of walking and jogging. *Journal of Orthopaedic Research*, 8(6), 814-823.

Gore, C., Hahn, A., Aughey, R., Martin, D., Ashenden, M., Clark, S., Garnham, A., Roberts, A., Slater, G., & McKenna, M. (2001). Live high: train low increases muscle buffer capacity and submaximal cycling efficiency. *Acta Physiol Scand*, 173, 275-286.

Hay, J. (1993). *The Biomechanics of Sports Techniques* (4th ed.). New Jersey: Prentice-Hall, Inc.

Hobara, H., Inoue, K., Gomi, K., Sakamoto, M., Muraoka, T., Iso, S., & Kanosue, K. (2009). Continuous change in spring-mass characteristics during a 400m sprint. *Journal of Science and Medicine in Sport,* 413, No. of Pages 6.

Hoyt, R., Knapik, J., Lanza, J., Jones, B., & Staab, J. (1994). Ambulatory foot contact monitor to estimate metabolic cost of human locomotion. *Journal of Applied Physiology*, 76(4), 1818-1822.

Jordan, K., Challis, J., & Newell, K. (2006). Long range correlations in the stride interval of running. *Gait and Posture*, 24 (1), 120-125.

Katayama, K., Sato, K., Matsuo, H., Ishida, K., Iwasaki, K. & Miyamura, M. (2004). Effect of intermittent hypoxia on oxygen uptake during submaximal exercise in endurance athletes. *European Journal of Applied Physiology*, 92(1-2), 74-83.

Kelly, G.M. (2005). GFIT technology: The potential for ergogenic gain**.** Retrieved from http://www.healthylegs.com

Kemmler, W., von Stengel, S., Kockritz, C., Mayhew, J., Wassermann, A., & Zapf, J. (2009). Effect of compression stockings on running performance in male runners. *Journal of Strength and Conditioning Research*, 23(1), 101-105.

Kraemer, W.J., Bush, J.A., Bauer, J.A., Triplett-McBride, N.T., Paxton, N.J., Clemson, A., Koziris, L.P., Mangino, L.C., Fry, A.C. & Newton, R.U. (1996). Influence of compression garments on vertical jump performance in NCAA Division I volleyball players. *Journal of Strength and Conditioning Research*, 10(3), 180-183.

Kraemer, W.J., Bush, J.A., Triplett-McBride, N.T., Koziris, L.P., Mangino, L.C., Fry, A.C., McBride, J.M., Johnston, J., Volek, J.S., Young, C.A., Gomez, A.L. & Newton, R.U. (1998). Compression garments: influence on muscle fatigue. *Journal of Strength and Conditioning Research*, 12(4), 211-215.

Kram, R. & Taylor, C.R. (1990) Energetics of running: a new perspective. *Nature*, 346, 265-267.

Lake, M. & Cavanagh, P. (1996). Six weeks of training does not change running mechanics or improve running economy. *Medicine and Science in Sports and Exercise*, 28(7), 860-869.

Larsen, H.B. (2003). Kenyan dominance in distance running. *Comparative Biochemistry and Physiology – Part A: Molecular and Integrative Physiology*, 136(1), 161-170.

Laymon, A., Lundgren, L., McKenzie, J., Wilhite, D., & Chapman, R. (2009). Running economy changes after altitude training: Role of running mechanics: 2360: Board #5 May 29 8:00 AM - 9:30 AM. *Medicine & Science in Sports & Exercise*, 41(5), 320.

Levine, B. & Stray-Gundersen, J. (1997). "Living high-training low": Effect of moderate altitude acclimatization with low-altitude training on performance. *Journal of Applied Physiology*, 83(1), 102-112.

Lohman, T., Roche, A., & Martorell, R. (1988). *Anthropometric Standardization Reference Manual*. Champaign, Illinois, Human Kinetics.

Lucia, A., Esteve-Lanao, J., Olivan, J., Gomez-Gallego, F., San Juan, A.F., Santiago, C., Perez, M., Chamorro-Vina, C. & Foster, C. (2006). Physiological characteristics of the best Eritrean runners—exceptional running economy. *Applied Physiology, Nutrition and Metabolism*, 31(5), 530-541.

McMahon, T. & Cheng, G. (1990). The mechanics of running: how does stiffness couple with speed? *Journal of Biomechanics*, 23 Suppl 1, 65-78.

McMahon, T.A., Valiant, G., & Frederick, G. (1987). Groucho running. *Journal of Applied Physiology*, 62(6), 2326-2337.

McMillan, G. (2006). *The McMillan Running Calculator*. Retrieved from http://www.mcmillanrunning.com/mcmillanrunningcalculator.htm

McNair, P. & Stanley, S. (1996). Effect of passive stretching and jogging on the series elastic muscle stiffness and range of motion of the ankle joint. *British Journal of Sports Medicine*, 30, 313-318.

Messier, S.P. & Cirillo, K.J. (1989). Effects of a verbal and visual feedback system on running technique, perceived exertion and running economy in female novice runners. *Journal of Sports Science*, 7(2), 113-126.

Morgan, D.W. & Martin, P.E. (1986). Effects of stride length alteration on racewalking economy. *Canadian Journal of Applied Sport Sciences*, 11(4), 211-217.

Paavolainen, L., Hakkinen, K., Hamalainen, I., Nummela, A., & Rusko, H. (1999). Explosive-strength training improves 5-km running time by improving running economy and muscle power. *Journal of Applied Physiology*, 86(5), 1527-1533.

Petray, C.K. & Krahenbuhl, G.S. (1985). Running training, instruction on running technique, and running economy in 10-year old males. *Research Quarterly for Exercise and Sport*, 56(3), 251-255.

Pohl, M. (2008). Gait *Analysis I*. ACSM, Indianapolis, IN.

Pollock, M.L. (1977). Submaximal and maximal working capacity of elite distance runners. Part 1: Cardiorespiratory aspects. *Annals of the New York Academy of Sciences*, 301, 310-322.

Revel Sports ®. (2009). Zensah training and muscle recovery/calf compression leg sleeves. Retrieved from http://www.revelsports.com

Sagal, P. (2009, March). Feel the squeeze: Sizing up the benefits of compression socks. *Runner's World*.

Saltin, B., Larsen, H., Terrados, N., Bangsbo, J., Bak, T., Kim, K., Svedenhag, J., & Rolf, C.J. (1995). Aerobic exercise capacity at sea level and at altitude in Kenyan boys, junior and senior runners compared with Scandinavian runners. *Scandinavian Journal of Medicine and Science in Sports*, 5(4), 209-221.

Saunders, P., Pyne, D., Telfor, R., & Hawley, J. (2004*a*). Factors affecting running economy in trained distance runners. *Sports Medicine*, 34(7), 465-485.

Saunders, P., Telford, R., Pyne, D., Cunningham, R., Gore, C., Hahn, A., & Hawley, J. (2004*b*). Improved running economy in elite runners after 20 days of simulated moderate-altitude exposure. *Journal of Applied Physiology*, 96, 931-937.

Stanton, R., Reaburn, P., & Humphries, B. (2004). The effect of short-term Swiss ball training on core stability and running economy. *Journal of Strength and Conditioning Research*, 18(3), 522-528.

Stray-Gundersen, J., Chapman, R. & Levine, B. (2001). "Living high-training low" altitude training improves sea level performance in male and female elite runners. *Journal of Applied Physiology*, 91, 1113-1120.

Storen, O., Helgerud, J., Stoa, E., & Hoff, J. (2008). Maximal strength training improves running economy in distance runners. *Medicine and Science in Sports and Exercise*, 40(6), 1087-1092.

United States of America Track & Field. (2003). Long Distance Running – State of the Sport. <www.usatf.org/news/specialReports/2003LDRStateOfTheSport.asp>.

Truijens, M., Rodriguez, F., Townsend, N., Stray-Gundersen, J., Gore, C. & Levine, B. (2008). The effect of intermittent hypobaric hypoxic exposure and sea level training on submaximal economy in well-trained swimmers and runners. *Journal of Applied Physiology*, 104, 328-337.

Tseh, W., Caputo, J. & Morgan, D.W. (2008). Influence of gait manipulation on running economy in female distance runners. *Journal of Sports Science and Medicine*, 7, 91-95.

Weston, A.R., Karamizrak, O., Smith, A., Noakes, T.D. & Myburgh, K.H. (1999). African runners exhibit greater fatigue resistance, lower lactate accumulation, and higher oxidative enzyme activity. *Journal of Applied Physiology*, 86, 915-923.

Weyand, P., Kelly, M., Blackadar, T., Darley, J.C., Oliver, S.R., Ohlenbusch, N.E., Joffe, S.W. & Hoyt, R.W. (2001). Ambulatory estimates of maximal aerobic power from foot-ground contact times and heart rates in running humans. *Journal of Applied Physiology*, 91, 451-458.

Weyand, P.G., Sternlight, D.B., Bellizzi, M.J. & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology*, 89, 1991-1999.

White, S. (2008). *The Use of Real-Time Feedback to Alter Movement Patterns*. ACSM, Indianapolis, IN.

Wilken, J. (2008). *The Use of Real-Time Feedback to Alter Movement Patterns*. ACSM, Indianapolis, IN.

Williams, K. & P. Cavanagh. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology*, 63(3), 1236-1245.

APPENDIX A

Raw Data, Tables, and Figures

	Rest		233-C		233-T		267-C		267-T		300-C		300-T	
Subject	**VO2**	**HR**	**VO2**	**HR**	**VO2**	**HR**	**VO2**	**HR**	**VO2**	**HR**	**VO2**	**HR**	**VO2**	**HR**
1	6.94		56.49	175	54.37	155	64.95	170	64.46	173	69.87	180	71.95	184
2	4.27	71	40.57	144	40.6	145	46.95	162	48.83	164	55.76	181	55.34	177
3*	7.07	72	56.89	149	57.38	152	60.45	163	64.67	165	66.63	175	72.52	179
4	8.28		55.81	155	55.41	163	63.33	172	63.63	173	73.48	182	71.04	181
5	6.5	86	53.04	162	51.46	171	60.65	175	60.6	185	67.19	193	68.74	194
6	5.43	66	52.99	135	53.51	130	60.56	146	59.31	145	73.05	162	75.96	158
7	4.82	59	38.23	*	37.55	*	47.03	*	46.55	*	54.71	*	53.28	*
8	5.55	80	41.57	*	41.07	*	47.81	*	48.07	*	55.57	*	56.79	*
9	7.84	72	49.64	141	47.5	142	53.68	145	54.44	145	62.92	158	63.77	156
10	5.09	70	43.57	136	43.8	136	51.67	151	49.26	152	60.5	169	58.49	166
11	4.57	58	44.8	157	46.37	139	54.69		56.04	157	62.34	167	62.78	170
12	4.48	53	48.91	129	48.5	130	57.7	148	58.02	148	66.49	158	65.61	160
13	4.93	66	40.04	116	39.91	122	46.09	131	46.07	132	53.56	145	54.97	149
14	4.76	61	40.59	128	39.34	130	48.57	154	45.55	139	57.56	170	54.67	156
15	5.75	72	45.96	151	49.17	159	52.87	163	55.46	174	58.98	177	60.92	180
16	7.47	76	48	158	49.46	145	53.86	169	54.12	168	59.58	179	58.85	179
AVG	**5.78**	**68.46**	**46.68**	**145.15**	**46.53**	**143.62**	**54.03**	**157.17**	**54.03**	**158.08**	**62.10**	**170.85**	**62.21**	**170.0**
SD	**1.31**	**9.30**	**6.01**	**16.39**	**5.87**	**14.72**	**6.23**	**13.45**	**6.38**	**16.03**	**6.58**	**12.92**	**7.13**	**13.5**

Table 6. Resting and submaximal oxygen consumption and heart rate data for all subjects.
* Equipment failure. Subject data is not included in mean or SD.

Table 7. Measured gait variables during control and treatment conditions for all subjects. *Equipment failure.

	Control						Treatment				
	GCTIME	**STRIDETIME**	**SWINGTIME**	**STRIDEFREQ**	**STRIDELENG**		**GCTIME**	**STRIDETIME**	**SWINGTIME**	**STRIDEFREQ**	**STRIDELENG**
Subject: TS											
233 m·min^{-1}											
Right foot	0.19	0.68	0.49	175.41	1.33		0.200	0.687	0.488	174.671	1.334
Left foot	0.21	0.69	0.47	175.20	1.33		0.209	0.687	0.479	174.670	1.334
Avg	0.202	0.685	0.482	175.306	1.329		0.204	0.687	0.483	174.671	1.334
267 m·min^{-1}											
Right foot	0.182	0.667	0.485	180.033	1.483		0.185	0.667	0.481	180.016	1.483
Left foot	0.191	0.667	0.476	179.965	1.484		0.187	0.667	0.479	180.004	1.483
Avg	0.187	0.667	0.480	179.999	1.483		0.186	0.667	0.480	180.010	1.483
300 m·min^{-1}											
Right foot	0.167	0.654	0.487	183.508	1.635		0.175	0.658	0.482	182.423	1.645
Left foot	0.177	0.654	0.476	183.606	1.634		0.176	0.657	0.482	182.526	1.644
Avg	0.172	0.654	0.481	183.557	1.635		0.176	0.658	0.482	182.475	1.644
Subject: TM											
233 m·min^{-1}											
Right foot	0.225	0.649	0.424	184.994	1.260		0.229	0.651	0.422	184.404	1.264
Left foot	0.233	0.650	0.417	184.662	1.262		0.233	0.651	0.419	184.216	1.265
Avg	0.229	0.649	0.420	184.828	1.261		0.231	0.651	0.420	184.310	1.264
267 m·min^{-1}											
Right foot	0.201	0.643	0.443	186.620	1.431		0.201	0.642	0.441	186.938	1.429
Left foot	0.205	0.644	0.440	186.304	1.433		0.204	0.642	0.438	186.900	1.429
Avg	0.203	0.644	0.441	186.462	1.432		0.202	0.642	0.440	186.919	1.429
300 m·min^{-1}											
Right foot	0.186	0.628	0.441	191.229	1.569		0.185	0.624	0.439	192.318	1.560
Left foot	0.170	0.627	0.457	191.387	1.568		0.165	0.624	0.459	192.345	1.560
Avg	0.178	0.627	0.449	191.308	1.568		0.175	0.624	0.449	192.332	1.560

	Control						Treatment				
	GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG		GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG
Subject: DF											
233 m·min^{-1}											
Right foot	0.215	0.665	0.450	182.647	1.292		0.224	0.661	0.437	181.540	1.284
Left foot	*	*	*	*	*		*	*	*	*	*
Avg											
267 m·min^{-1}											
Right foot	0.190	0.631	0.441	190.229	1.404		0.198	0.654	0.456	183.532	1.455
Left foot	*	*	*	*	*		*	*	*	*	*
Avg											
300 m·min^{-1}											
Right foot	*	*	*	*	*		0.185	0.641	0.457	187.179	1.603
Left foot	*	*	*	*	*		*	*	*	*	*
Avg											
Subject: JH											
233 m·min^{-1}											
Right foot	0.226	0.712	0.486	168.608	1.382		0.215	0.730	0.514	164.447	1.417
Left foot	0.192	0.712	0.519	168.535	1.383		0.191	0.730	0.539	164.512	1.416
Avg	0.209	0.712	0.502	168.572	1.382		0.203	0.730	0.526	164.479	1.417
267 m·min^{-1}											
Right foot	0.171	0.694	0.523	173.049	1.543		0.169	0.701	0.532	171.173	1.560
Left foot	0.180	0.693	0.513	173.109	1.543		0.177	0.707	0.530	169.775	1.573
Avg	0.175	0.693	0.518	173.079	1.543		0.173	0.704	0.531	170.474	1.567
300 m·min^{-1}											
Right foot	0.163	0.685	0.523	175.183	1.713		*	*	*	*	*
Left foot	0.166	0.685	0.519	175.089	1.714		0.170	0.681	0.511	176.249	1.702
Avg	0.165	0.685	0.521	175.136	1.713						

	Control						Treatment				
	GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG		GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG
Subject: DS											
233 m·min^{-1}											
Right foot	0.209	0.757	0.548	158.472	1.470		0.213	0.765	0.552	156.860	1.485
Left foot	0.193	0.757	0.565	158.452	1.471		0.198	0.765	0.567	156.855	1.486
Avg	0.201	0.757	0.556	158.462	1.470		0.206	0.765	0.559	156.858	1.485
267 m·min^{-1}											
Right foot	0.198	0.731	0.533	164.155	1.627		0.197	0.719	0.523	166.897	1.600
Left foot	0.178	0.731	0.553	164.121	1.627		0.183	0.719	0.536	166.899	1.600
Avg	0.188	0.731	0.543	164.138	1.627		0.190	0.719	0.529	166.898	1.600
300 m·min^{-1}											
Right foot	0.188	0.695	0.507	172.788	1.736		0.186	0.691	0.505	173.605	1.728
Left foot	0.177	0.695	0.517	172.763	1.737		0.179	0.691	0.512	173.604	1.728
Avg	0.183	0.695	0.512	172.775	1.736		0.183	0.691	0.509	173.604	1.728
Subject: JK											
233 m·min^{-1}											
Right foot	0.180	0.733	0.553	165.618	1.423		0.189	0.719	0.530	167.122	1.396
Left foot	0.207	0.734	0.526	165.358	1.424		0.204	0.721	0.516	166.588	1.399
Avg	0.194	0.733	0.540	165.488	1.424		0.197	0.720	0.523	166.855	1.398
267 m·min^{-1}											
Right foot	0.182	0.701	0.519	171.372	1.559		0.185	0.693	0.507	173.244	1.542
Left foot	0.189	0.702	0.513	170.850	1.563		0.184	0.692	0.508	173.489	1.540
Avg	0.186	0.702	0.516	171.111	1.561		0.185	0.693	0.508	173.367	1.541
300 m·min^{-1}											
Right foot	0.159	0.673	0.515	178.329	1.683		0.151	0.666	0.528	180.377	1.665
Left foot	0.170	0.671	0.501	178.727	1.679		0.159	0.670	0.511	179.217	1.674
Avg	0.165	0.672	0.508	178.528	1.681		0.155	0.668	0.519	179.797	1.670

	Control						Treatment				
	GCTIME	**STRIDETIME**	**SWINGTIME**	**STRIDEFREQ**	**STRIDELENG**		**GCTIME**	**STRIDETIME**	**SWINGTIME**	**STRIDEFREQ**	**STRIDELENG**
Subject: TG											
233 $m\cdot min^{-1}$											
Right foot	0.193	0.703	0.510	170.609	1.366		0.196	0.702	0.506	170.832	1.364
Left foot	0.196	0.703	0.507	170.613	1.366		0.197	0.718	0.521	169.007	1.393
Avg	0.195	0.703	0.509	170.611	1.366		0.197	0.710	0.513	169.919	1.379
267 $m\cdot min^{-1}$											
Right foot	0.180	0.666	0.486	180.168	1.482		0.179	0.667	0.488	180.017	1.483
Left foot	0.182	0.666	0.484	180.141	1.482		0.186	0.667	0.481	179.984	1.484
Avg	0.181	0.666	0.485	180.155	1.482		0.182	0.667	0.484	180.000	1.483
300 $m\cdot min^{-1}$											
Right foot	0.173	0.636	0.463	188.764	1.589		0.176	0.635	0.459	188.934	1.588
Left foot	0.177	0.636	0.459	188.825	1.589		0.178	0.635	0.457	188.889	1.588
Avg	0.175	0.636	0.461	188.794	1.589		0.177	0.635	0.458	188.911	1.588
Subject: JP											
233 $m\cdot min^{-1}$											
Right foot	0.211	0.714	0.503	168.210	1.386		0.213	0.716	0.503	167.580	1.390
Left foot	0.207	0.714	0.507	168.098	1.386		0.209	0.716	0.507	167.550	1.391
Avg	0.209	0.714	0.505	168.154	1.386		0.211	0.716	0.505	167.565	1.391
267 $m\cdot min^{-1}$											
Right foot	0.196	0.699	0.503	171.590	1.556		0.202	0.702	0.500	170.972	1.562
Left foot	0.190	0.699	0.510	171.591	1.556		0.195	0.702	0.507	170.986	1.562
Avg	0.193	0.699	0.507	171.591	1.556		0.198	0.702	0.503	170.979	1.562
300 $m\cdot min^{-1}$											
Right foot	0.185	0.683	0.499	175.595	1.709		0.176	0.683	0.507	175.813	1.706
Left foot	0.179	0.683	0.506	175.720	1.707		0.179	0.683	0.503	175.783	1.707
Avg	0.182	0.683	0.503	175.658	1.708		0.178	0.683	0.505	175.798	1.707

	Control						Treatment				
	GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG		GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG
Subject: CH											
233 m·min^{-1}											
Right foot	0.187	0.720	0.534	166.569	1.399		0.198	0.732	0.534	163.959	1.421
Left foot	0.191	0.720	0.529	166.595	1.399		0.191	0.732	0.540	163.975	1.421
Avg	0.189	0.720	0.531	166.582	1.399		0.194	0.732	0.537	163.967	1.421
267 m·min^{-1}											
Right foot	0.183	0.704	0.521	170.402	1.567		0.184	0.710	0.526	168.996	1.580
Left foot	0.178	0.704	0.526	170.434	1.567		0.185	0.710	0.526	168.960	1.580
Avg	0.180	0.704	0.524	170.418	1.567		0.184	0.710	0.526	168.978	1.580
300 m·min^{-1}											
Right foot	0.171	0.683	0.513	175.751	1.707		0.171	0.686	0.515	174.943	1.715
Left foot	0.174	0.683	0.510	175.677	1.708		0.172	0.686	0.514	174.926	1.715
Avg	0.172	0.683	0.511	175.714	1.707		0.171	0.686	0.515	174.935	1.715
Subject: JS											
233 m·min^{-1}											
Right foot	0.226	0.741	0.515	162.022	1.438		0.224	0.730	0.506	164.381	1.418
Left foot	0.220	0.741	0.521	162.028	1.438		0.217	0.730	0.513	164.394	1.418
Avg	0.223	0.741	0.518	162.025	1.438		0.221	0.730	0.510	164.387	1.418
267 m·min^{-1}											
Right foot	0.204	0.710	0.506	169.213	1.579		0.208	0.717	0.508	167.478	1.594
Left foot	0.201	0.709	0.508	169.269	1.578		0.198	0.717	0.518	167.570	1.594
Avg	0.203	0.709	0.507	169.241	1.579		0.203	0.717	0.513	167.524	1.594
300 m·min^{-1}											
Right foot	0.188	0.703	0.515	170.721	1.757		0.189	0.699	0.510	171.730	1.747
Left foot	0.190	0.703	0.514	170.670	1.759		0.185	0.698	0.515	171.915	1.746
Avg	0.189	0.703	0.514	170.696	1.758		0.187	0.699	0.513	171.822	1.747

	Control						Treatment				
	GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG		GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG
Subject: YS											
233 m·min^{-1}											
Right foot	0.186	0.696	0.510	172.416	1.351		0.181	0.703	0.522	170.766	1.365
Left foot	0.184	0.696	0.518	172.340	1.352		0.183	0.703	0.519	170.668	1.365
Avg	0.185	0.696	0.514	172.378	1.352		0.182	0.703	0.521	170.717	1.365
267 m·min^{-1}											
Right foot	0.168	0.689	0.521	174.170	1.533		0.172	0.685	0.513	175.244	1.524
Left foot	0.170	0.690	0.523	174.034	1.534		0.172	0.685	0.515	175.297	1.523
Avg	0.169	0.689	0.522	174.102	1.534		0.172	0.685	0.514	175.270	1.523
300 m·min^{-1}											
Right foot	0.159	0.674	0.515	178.096	1.685		0.160	0.673	0.513	178.389	1.682
Left foot	0.159	0.675	0.516	177.913	1.686		0.159	0.674	0.527	178.031	1.685
Avg	0.159	0.674	0.515	178.004	1.685		0.159	0.673	0.520	178.210	1.684
Subject: DRS											
233 m·min^{-1}											
Right foot	0.217	0.708	0.491	169.502	1.375		0.202	0.712	0.510	168.539	1.383
Left foot	0.209	0.709	0.499	169.369	1.376		0.208	0.712	0.504	168.505	1.383
Avg	0.213	0.708	0.495	169.436	1.375		0.205	0.712	0.507	168.522	1.383
267 m·min^{-1}											
Right foot	0.199	0.701	0.502	171.186	1.560		0.201	0.702	0.501	170.922	1.562
Left foot	0.194	0.701	0.507	171.139	1.560		0.196	0.703	0.507	170.819	1.563
Avg	0.197	0.701	0.504	171.162	1.560		0.199	0.702	0.504	170.870	1.563
300 m·min^{-1}											
Right foot	0.183	0.695	0.511	172.710	1.737		0.190	0.700	0.509	171.510	1.749
Left foot	0.183	0.695	0.512	172.715	1.737		0.185	0.700	0.515	171.542	1.749
Avg	0.183	0.695	0.512	172.712	1.737		0.188	0.700	0.512	171.526	1.749

	Control						Treatment				
	GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG		GCTIME	STRIDETIME	SWINGTIME	STRIDEFREQ	STRIDELENG
Subject: MF											
233 m·min^{-1}											
Right foot	0.184	0.695	0.511	172.752	1.349		0.184	0.694	0.510	172.995	1.347
Left foot	0.219	0.711	0.492	170.576	1.380		0.225	0.693	0.469	173.150	1.346
Avg	0.202	0.703	0.501	171.664	1.365		0.204	0.693	0.489	173.073	1.346
267 m·min^{-1}											
Right foot	0.209	0.673	0.463	178.353	1.497		0.202	0.673	0.472	178.302	1.498
Left foot	0.201	0.673	0.472	178.308	1.498		0.208	0.673	0.465	178.290	1.498
Avg	0.205	0.673	0.468	178.330	1.498		0.205	0.673	0.468	178.296	1.498
300 m·min^{-1}											
Right foot	0.192	0.654	0.462	183.404	1.636		0.187	0.653	0.466	183.811	1.632
Left foot	0.177	0.654	0.477	183.444	1.636		0.180	0.653	0.473	183.921	1.631
Avg	0.185	0.654	0.469	183.424	1.636		0.183	0.653		183.866	1.632
Subject: JF											
233 m·min^{-1}											
Right foot	0.191	0.631	0.439	190.334	1.225		0.190	0.637	0.447	188.353	1.237
Left foot	0.193	0.642	0.448	188.773	1.246		0.195	0.637	0.442	188.355	1.237
Avg	0.192	0.636	0.444	189.554	1.235		0.192	0.637	0.445	188.354	1.237
267 m·min^{-1}											
Right foot	0.178	0.620	0.442	193.530	1.380		0.176	0.621	0.445	193.248	1.382
Left foot	0.182	0.620	0.439	193.463	1.380		0.183	0.621	0.438	193.160	1.382
Avg	0.180	0.620	0.440	193.496	1.380		0.180	0.621	0.441	193.204	1.382
300 m·min^{-1}											
Right foot	0.170	0.619	0.449	193.927	1.547		0.171	0.619	0.448	194.000	1.547
Left foot	0.170	0.619	0.449	193.919	1.547		0.171	0.619	0.447	193.959	1.547
Avg	0.170	0.619	0.449	193.923	1.547		0.171	0.619	0.447	193.980	1.547

	Control						Treatment				
	GCTIME	**STRIDETIME**	**SWINGTIME**	**STRIDEFREQ**	**STRIDELENG**		**GCTIME**	**STRIDETIME**	**SWINGTIME**	**STRIDEFREQ**	**STRIDELENG**
Subject: EB											
233 $m \cdot min^{-1}$											
Right foot	0.192	0.770	0.578	155.866	1.495		0.190	0.744	0.554	161.274	1.445
Left foot	0.192	0.770	0.578	155.888	1.495		0.201	0.744	0.543	161.256	1.445
Avg	0.192	0.770	0.578	155.877	1.495		0.196	0.744	0.548	161.265	1.445
267 $m \cdot min^{-1}$											
Right foot	0.182	0.757	0.576	158.467	1.685		0.179	0.744	0.564	161.401	1.654
Left foot	0.178	0.757	0.580	158.542	1.684		0.174	0.743	0.570	161.436	1.654
Avg	0.180	0.757	0.578	158.505	1.685		0.176	0.743	0.567	161.418	1.654
300 $m \cdot min^{-1}$											
Right foot	0.168	0.728	0.560	164.805	1.820		0.166	0.722	0.556	166.132	1.806
Left foot	0.164	0.728	0.564	164.811	1.820		0.164	0.722	0.558	166.181	1.805
Avg	0.166	0.728	0.562	164.808	1.820		0.165	0.722	0.557	166.156	1.806
Subject: JR											
233 $m \cdot min^{-1}$											
Right foot	0.202	0.711	0.509	168.843	1.380		0.200	0.710	0.510	169.018	1.379
Left foot	0.212	0.711	0.499	168.827	1.380		0.211	0.710	0.499	168.993	1.379
Avg	0.207	0.711	0.504	168.835	1.380		0.205	0.710	0.505	169.006	1.379
267 $m \cdot min^{-1}$											
Right foot	0.187	0.690	0.502	174.016	1.534		0.185	0.686	0.501	174.955	1.526
Left foot	0.198	0.690	0.491	174.001	1.535		0.195	0.686	0.491	174.937	1.526
Avg	0.193	0.690	0.497	174.009	1.534		0.190	0.686	0.496	174.946	1.526
300 $m \cdot min^{-1}$											
Right foot	0.176	0.661	0.485	181.570	1.652		0.175	0.661	0.486	181.665	1.652
Left foot	0.186	0.661	0.476	181.507	1.653		0.186	0.661	0.475	181.648	1.652
Avg	0.181	0.661	0.480	181.538	1.653		0.180	0.661	0.481	181.656	1.652

Subject	233 m·min^{-1}		268 m·min^{-1}		300 m·min^{-1}	
	C	T	C	T	C	T
	K_{vert} (kN·m^{-1})	K_{vert} (kN·m^{-1})	K_{vert} (kN·m^{-1})	K_{vert} (kN·m^{-1})	K_{vert} (kN·m^{-1})	K_{vert} (kN·m^{-1})
1	28.45068	27.74355	34.96567	35.47908	43.98507	41.3696
2	34.51337	34.56752	40.82928	40.89499	48.38236	47.46253
3	39.69576	37.26582	46.84319	44.63746	48.29022	48.08227
6	21.54964	21.05965	30.69065	31.05186	44.31179	46.40558
7	33.95827	33.09468	42.27214	40.86888	49.32496	52.56913
8	45.59248	42.80256	51.6028	48.72339	57.37689	58.64435
9	45.28288	42.42409	49.14101	49.3028	67.47221	81.49897
10	40.75538	39.86369	48.20981	47.42012	50.93924	49.15597
11	25.90748	26.25828	32.90361	33.18105	40.36286	41.49337
12	42.3558	44.7372	54.91401	51.71681	64.31205	64.78785
13	37.2879	35.68884	34.1566	34.1566	45.15586	46.50913
14	31.06473	35.03889	38.87118	37.81914	48.06997	44.65678
15	52.43815	47.63479	63.38245	65.68298	76.69445	77.45419
16	32.60474	33.52054	39.03558	40.67588	45.33441	46.09359
AVG	**36.53266**	**35.83572**	**43.41557**	**42.97222**	**52.14374**	**53.29881**

Table 8. Estimated vertical stiffness (kN·m^{-1}) during all speeds and experimental conditions.

Measure	Partial eta squared	Power
VO_2 14	.000	.050
VO_2 16	.000	.050
VO_2 18	.013	.065
t_c 14	.025	.080
t_c 16	.005	.056
t_c 18	.061	.128
t_{sw} 14	.057	.123
t_{sw} 16	.151	.270
t_{sw} 18	.063	.131
t_{st} 14	.033	.091
t_{st} 16	.031	.088
t_{st} 18	.038	.097
SF 14	.005	.056
SF 16	.036	.095
SF 18	.065	.135
SL 14	.032	.089
SL16	.042	.102
SL18	.050	.114

Table 9. Power and effect size of non-significant variables, control to treatment. Running speeds are 14, 16, and 18 $km \cdot hr^{-1}$.

Subject	Calf circ. (in)	Average Output (V)	SD
1	13	-3.670	0.262
2	14.1	-3.513	0.070
3	14	-4.136	0.192
4	12.6	-4.219	0.148
5	13.75	-4.479	0.014
6	13.4	-4.056	0.277
7	13.75	-3.573	0.178
8	14.9	-3.597	0.347
9	13.9	-2.213	0.650
10	13.75	-3.655	0.427
11	14.5	-2.597	0.412
12	13.5	-3.781	0.311
13	14	-3.134	0.458
14	13.7	-2.441	0.885
15	14.9	-3.536	0.515
16	14.2	-2.911	0.762

Table 10. Subject calf circumference and voltage output (mean and SD) from pressure sensor placed between calf and sleeve.

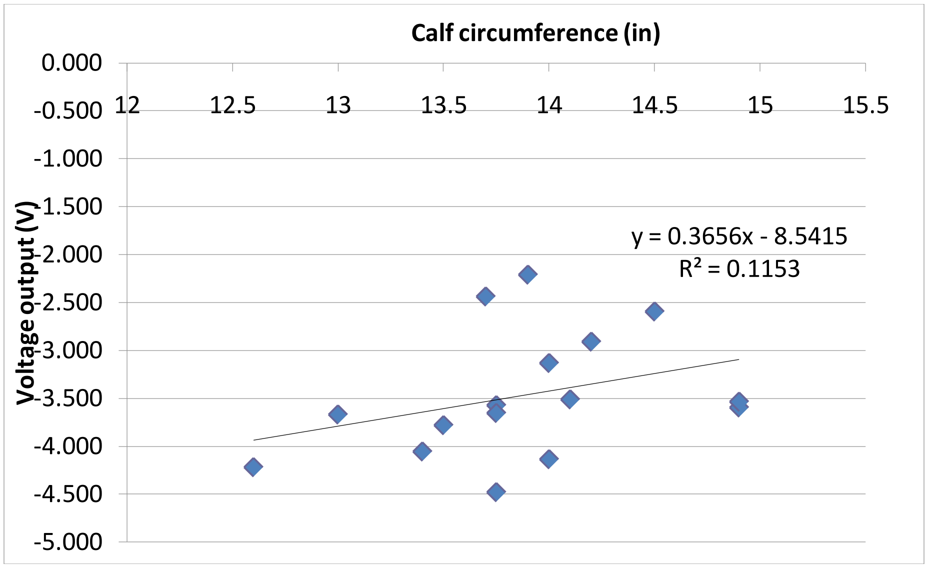
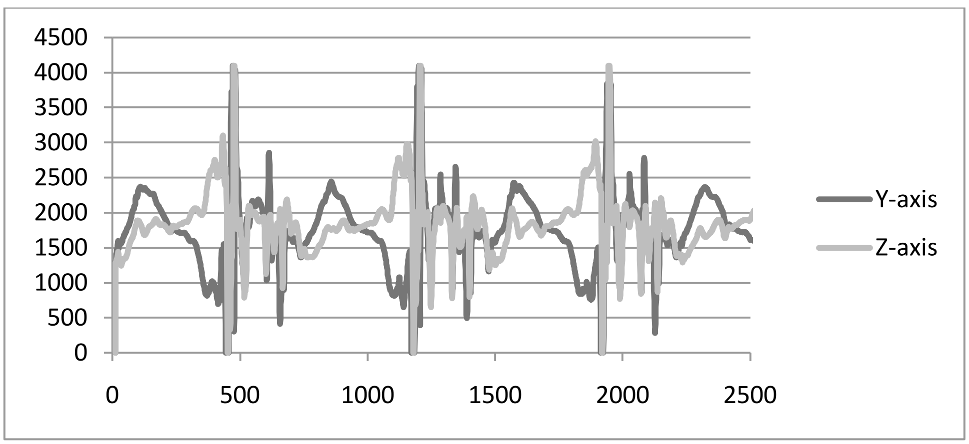
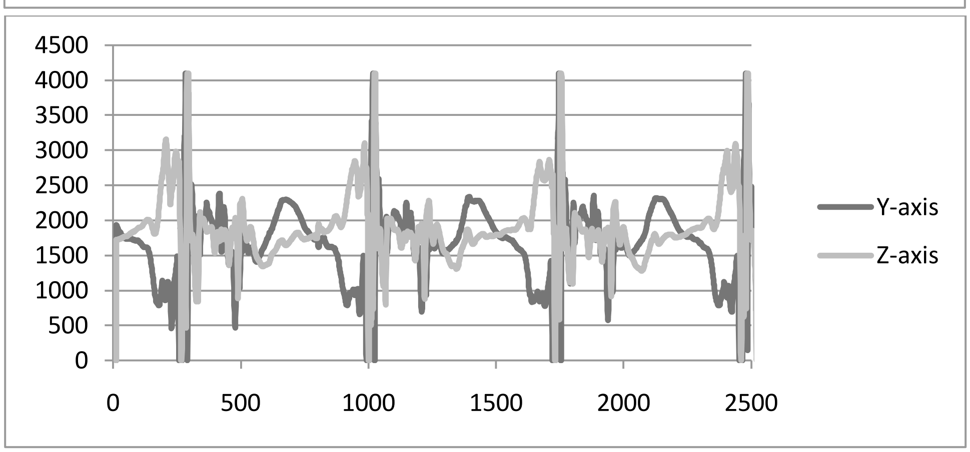


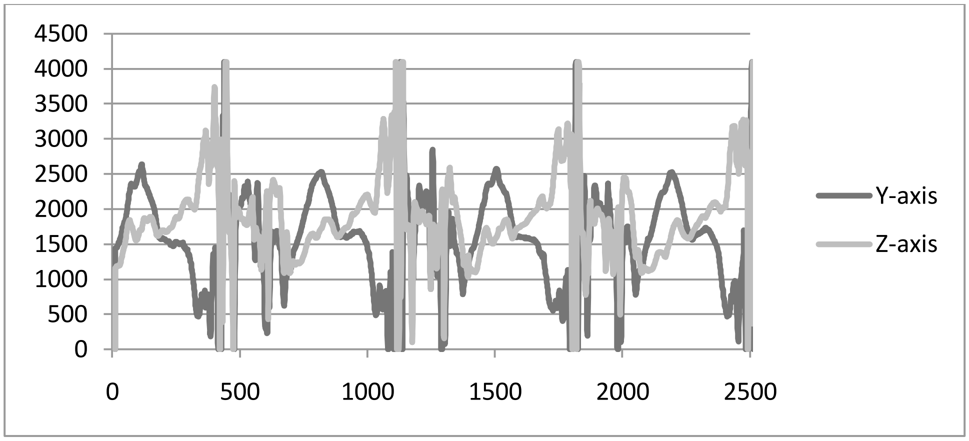
Figure 7. Relationship between calf circumference and pressure sensor voltage output.



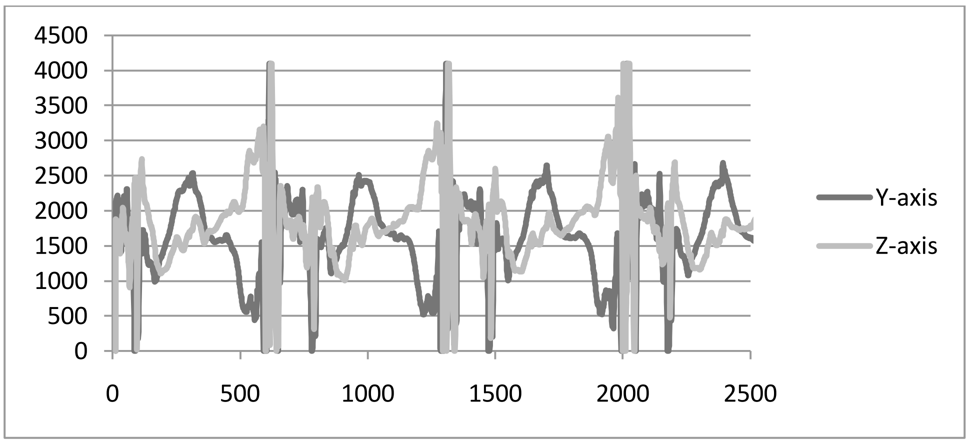
(a)



(b)



(c)



(d)

Figure 8. Accelerometric waveform output for subject #14 (the subject who exhibited the greatest negative ΔVO_2 with compression treatment) during the two experimental conditions at two speeds: (a) 233 m·min^{-1} control, (b) 233 m·min^{-1} treatment, (c) 300 m·min^{-1} control, (d) 300 m·min^{-1} treatment. The graph's x-axis is speed (ms), the y-axis is accelerometer output.

APPENDIX B

Indiana University Institutional Review Board Approval

INDIANA UNIVERSITY BLOOMINGTON INSTITUTIONAL REVIEW BOARD (IRB) REVIEW

DOCUMENTATION OF REVIEW AND APPROVAL (DRA)

0904000251
(IRB Office will assign)

SECTION I: INVESTIGATOR INFORMATION

Principal Investigator: Laymon, Abigail S. **Department:** HPER - Kinesiology
(Last, First, Middle Initial------must have faculty/staff status or faculty sponsor must sign)

Building/Room No.: HPER 070 Phone: (812) 855-7556 E-Mail: aslaymon@indiana.edu

Contact Information:

Name: (Faculty Sponsor: Dr. Jeanne Johnston) Address: HPER 112, 1025 E 7th St. Bloomington, 47405
Phone: (812) 855-7556
Fax: E-Mail: (jdjohnst@indiana.edu)

STUDENT PROTOCOLS ONLY: Name of the Student: Phone:
E-Mail:

Protocol Title: **Lower leg compression sleeves: Influence on running mechanics and economy in highly trained distance runners**

Sponsor/Funding Agency: N/A PI on Grant:
Sponsor Protocol #/Grant #: Project Duration: From: -
Sponsor Type: ☐ Federal; ☐ State; ☐ Industry*; ☐ Not-for-Profit; ☐ Unfunded; ☐ Internally Funded
Grant Title (if different from project title):

SECTION II: TYPE OF REVIEW

☒ Expedited Review
☐ Full Board Review

SECTION III: SPECIAL SUBJECT POPULATIONS INVOLVED IN THE RESEARCH

☐ Children
☐ Cognitively Impaired
☐ Economically/ Educationally Disadvantaged
☐ Human Fetuses (or Fetal Tissue) or Neonates
☐ Pregnant Women
☐ Prisoners

SECTION IV: DOCUMENTS INCLUDED WITH RESEARCH SUBMISSION

☒ Informed Consent Document(s), dated:
# of consent document(s):
☒ Summary Safeguard Statement (SSS), dated:
☐ Authorization(s), dated:
☐ Protocol, dated:
☐ Other, description:
☐ Assent Document(s), dated:
# of assent document(s):
☒ Recruitment Materials, dated:
☒ Advertisement(s), dated:
☒ Surveys, Questionnaires, dated:

You only need to list document dates if they are required by the investigator or sponsor.

SECTION V: INVESTIGATOR STATEMENT OF COMPLIANCE

By submitting this form, I assure the Board that all procedures performed under the project will be conducted in strict accordance with those federal regulations, Indiana University policies that govern research involving human subjects. I acknowledge that I have the resources required to conduct research in a way that will protect the rights and welfare of participants. I agree to submit *any* deviation from the project (e.g. change in principal investigator, research methodology, subject recruitment procedures, etc.) to the Board in the form of an amendment for IRB approval prior to implementation.

Signature of Investigator: Received by email Date: April 16, 2009

SECTION VI: IRB APPROVAL

This research project, including all documents included with the submission (e.g., informed consent statement, authorization, and/or waiver of authorization) has been reviewed and approved by the Indiana University Bloomington Institutional Review Board for a maximum of a one year period beyond the final approval date unless otherwise indicated as follows:____________________

Authorized IRB Signature: Sara Brand IRB Approval Date: 5/13/09

INDIANA UNIVERSITY

OFFICE OF RESEARCH ADMINISTRATION

To: Abigail S. Laymon
HPER-Kinesiology

From: IUB Human Subjects Office
Office of Research Administration – Indiana University

Date: May 13, 2009

RE: **PROTOCOL APPROVAL – EXPEDITED – 4**

Protocol Title:	Lower Leg Compression sleeves: Influence on Running Mechanics and Economy in Highly Trained Distance Runners
Protocol #:	0904000251
Sponsor:	N/A

The above-referenced protocol was reviewed by the IRB. The protocol meets the requirements for expedited review pursuant to §46.110, Category 4. The protocol is approved for a period of **May 13, 2009** through **May 12, 2010**. This approval does not replace any departmental or other approvals that may be required.

If you submitted and/or are required to provide participants with an informed consent document, study information sheet, or other documentation, a **copy of the approved stamped document is enclosed and <u>must be used</u>**.

As the principal investigator (or faculty sponsor in the case of a student protocol) of this study, you assume the following responsibilities:

1. **CONTINUING REVIEW:** Federal regulations require that all research be reviewed at least annually. You may receive a "Continuation Renewal Reminder" approximately two months prior to the expiration date; however, it is the Principal Investigator's responsibility to obtain continued approval from the IRB ***before*** **May 13, 2010**. If the IRB does not grant continued approval by this date, the study will automatically expire, requiring all research activities, including enrollment of new participants, interaction and intervention with current participants, and analysis of identified data to stop.

2. **AMENDMENTS:** Any proposed changes to the research study must be reported to the IRB prior to implementation. Only after approval has been granted by the IRB can these changes be implemented. An amendment form can be obtained at http://researchadmin.iu.edu/HumanSubjects/IUB/hs_forms.html.

3. **ADVERTISEMENTS:** Only IRB-approved advertisements may be used to recruit participants for the study. If you submitted an advertisement with your study submission, an approved stamped copy is provided with the approval. To request approval of an advertisement in the future, please submit an amendment, explaining the mode of communication and information to be contained in the advertisement.

4. **COMPLETION:** Prompt notification must be made to the IRB when the study is completed (i.e. there is no further subject enrollment, no further interaction or intervention with current participants, including follow-up, and no further analysis of identified data). To notify the IRB of study closure, please obtain a close-out form at http://researchadmin.iu.edu/HumanSubjects/IUB/hs_forms.html.

5. **LEAVING THE INSTITUTION:** The IRB must be notified of the disposition of the study when the principal investigator (or faculty sponsor in the case of a student project] leaves the institution.

6. **VULNERABLE POPULATIONS:** Please note that there are special requirements for the inclusion of vulnerable populations (i.e. children and minors, prisoners, pregnant women and human fetuses, and cognitively impaired) in research. You may not enroll or otherwise include an individual who is or becomes a member of a vulnerable population while enrolled in the research if that vulnerable population has not already been approved by the IRB for enrollment. For additional information on the requirements for including vulnerable populations in research, please refer to http://research.iu.edu/rschcomp/hmpg.html .

Note: SOPs exist covering a variety of topics that may be relevant to the conduct of your research. For more information on the relevant policies and procedures, go to http://research.iu.edu/rschcomp/hmpg.html.

You should retain a copy of this letter and any associated approved study documents (e.g. informed consent or advertisements) for your records. All documentation related to this study must be maintained in your files for audit purposes for at least three years after closure of the research; however, please note that research studies subject to HIPAA may have different requirements regarding file storage after closure. Please refer to the project title and number in future correspondence with our office. Additional information is available on our website at http://researchadmin.iu.edu/HumanSubjects/IUB/hs_home.html. Please contact our office if you have questions or need further assistance.

Thank you.

APPENDIX C

Informed Consent Statement

IRB Study #0904000251

INDIANA UNIVERSITY BLOOMINGTON

INFORMED CONSENT STATEMENT

Lower leg compression sleeves: Influence on running mechanics and economy

You are invited to participate in a research study designed to investigate how wearing lower leg compression sleeves affects running mechanics and running economy. You were selected as a possible subject by nature of being a highly trained male distance runner. We ask that you read this form and ask any questions you may have before agreeing to be in the study.

The study is being conducted by Abigail Laymon, a master's student in the Department of Kinesiology at Indiana University, with assistance from co-investigators, Drs. Jeanne Johnston and Robert Chapman.

STUDY PURPOSE

The purpose of this study is to examine whether wearing lower leg compression sleeves evokes changes in running economy due to altered gait mechanics.

NUMBER OF PEOPLE TAKING PART IN THE STUDY:

If you agree to participate, you will be one of twenty male subjects who will be participating in this research.

PROCEDURES FOR THE STUDY:

If you agree to be in the study, you will be asked to complete a single testing session, lasting approximately 60 minutes in duration. Testing will take place in the Human Performance Laboratories in the Health, Physical Education, and Recreation (HPER) building on the Indiana University Bloomington campus.

Prior to participation, you will be asked to complete a medical questionnaire (PAR-Q) that asks general questions about your physical health. You will also be asked to complete a survey regarding your perceptions of lower leg compression garments. To participate in this study, you must be a highly trained male distance runner, between the ages of 18-30 years old, currently training at a typical volume and intensity at least five days/week, and having raced a 5000m or equivalent time of <16:30 (min:s) in the past 12 months. You also must be free from potential factors related to heart, lung, or kidney disease, or the possibility of being pregnant (as determined by the PAR-Q medical questionnaire).

For all testing, you will be fitted with accelerometer devices. These devices measure 2.25 in x 1.75 in x 1 in and weigh about 4 ounces. The devices will be attached to the top of both of your shoes, utilizing plastic ties.

The testing session will include two separate running economy tests, one while wearing lower leg compression sleeves (Zensah Training and Muscle Recovery Leg Sleeves) and one without compression sleeves, with 10 minutes of rest between trials. Before each trial you will also have a 5-10 minute warm up period at a gentle pace that you select. Gait variables will be measured during the last 30 seconds of each four-minute stage of the running economy test. For all testing, you will wear your own lightweight racing flats.

Standard running economy protocol
Prior to the running economy testing your height and weight will be taken. After the warm up period, the first running economy test will begin. Running economy will be determined by measuring your oxygen consumption at three constant submaximal speeds of 6:55 min/mile, 5:59 min/mile, and 5:21 min/mile pace on the treadmill. You will run for four minutes at each speed, running continuously from one stage to the next. To get measures of oxygen consumption, you will wear a noseclip and breathe through a mouthpiece connected to a two-way valve. You are free to indicate discomfort and discontinue participation at any time.

RISKS OF TAKING PART IN THE STUDY:

While on the study, the risks, side effects, and/or discomforts are minimal. There is minimal risk from performing exercise bouts at submaximal workloads. Highly trained distance runners will be used to running at the submaximal speeds utilized in this study. During the running bouts, the subject may feel muscle fatigue, cramping, muscle strain or soreness.

There are no known or anticipated risks of wearing accelerometer devices on the shoe.

There is a potential risk of falling when running on a treadmill, particularly at fast speeds; however, as the subjects will all be trained distance runners who are a) used to running at the speeds indicated, and b) often familiar with running on a treadmill, the risk of falling from the treadmill is low.

To minimize any potential risks, standardized testing procedures will be used to minimize the risks associated with these tests. The principal investigator and co-investigators will be trained in First Aid/CPR. Noseclips and mouthpieces used during testing sessions will be soaked in Cidex antibacterial solution between subjects. Chairs will be next to the treadmill in case a subject feels lightheaded or needs to sit down at any time during or after testing.

Additional risks for all testing include the possible loss of confidentiality.

You are free to indicate discomfort and discontinue participation at any time.

BENEFITS OF TAKING PART IN THE STUDY:

The benefits to participation that are reasonable to expect are a) information regarding individual running economy and how it compares to other highly trained distance runners, and b) information as to how lower leg compression sleeves affect running mechanics, running economy, and potentially race performance.

ALTERNATIVES TO TAKING PART IN THE STUDY:

An alternative to participating in the study is to choose not to participate.

CONFIDENTIALITY

Efforts will be made to keep your personal information confidential. We cannot guarantee absolute confidentiality. Your personal information may be disclosed if required by law. Your identity will be held in confidence in reports in which the study may be published and databases in which results may be stored.

Organizations that may inspect and/or copy your research records for quality assurance and data analysis include groups such as the study investigator and his/her research associates, the IUB Institutional Review Board or its designees, and (as allowed by law) state or federal agencies, specifically the Office for Human Research Protections (OHRP) and the Food and Drug Administration (FDA), if applicable, the National Institutes of Health (NIH) [for research funded or supported by NIH], etc., who may need to access your medical and/or research records.

PAYMENT

You will not receive payment for taking part in this study.

COMPENSATION FOR INJURY

In the event of physical injury resulting from your participation in this research, necessary medical treatment will be provided to you and billed as part of your medical expenses. Costs not covered by your health care insurer will be your responsibility. Also, it is your responsibility to determine the extent of your health care coverage. There is no program in place for other monetary compensation for such injuries. However, you are not giving up any legal rights or benefits to which you are otherwise entitled.

CONTACTS FOR QUESTIONS OR PROBLEMS

For questions about the study or a research-related injury, contact the researcher Abigail Laymon at (812) 855-7556.

For questions about your rights as a research participant or to discuss problems, complaints or concerns about a research study, or to obtain information, or offer input, contact the IUB Human Subjects office, 530 E Kirkwood Ave, Carmichael Center, L03, Bloomington IN 47408, 812-855-3067 or by email at iub_hsc@indiana.edu

VOLUNTARY NATURE OF STUDY

Taking part in this study is voluntary. You may choose not to take part or may leave the study at any time. Leaving the study will not result in any penalty or loss of benefits to which you are entitled. Your decision whether or not to participate in this study will not affect your current or future relations with the investigator.

SUBJECT'S CONSENT

In consideration of all of the above, I give my consent to participate in this research study.

I will be given a copy of this informed consent document to keep for my records. I agree to take part in this study.

Subject's Printed Name: ____

Subject's Signature: ______________________________ **Date**:__________
(must be dated by the subject)

Printed Name of Person Obtaining Consent:______________________________

Signature of Person Obtaining Consent:____________________ **Date**:__________

APPENDIX D

Modified Physical Activity Readiness Questionnaire

Modified Physical Activity Readiness Questionnaire (PAR-Q)

Name			**Date**
DOB	**Age**	**Home Phone**	**Work Phone**

Regular exercise is associated with many health benefits, yet any change of activity may increase the risk of injury. Please read each question carefully and answer every question honestly:

Yes	**No**	**1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
Yes	**No**	**2. Do you feel pain in your chest when you do physical activity?**
Yes	**No**	3. **In the past month, have you had chest pain when you were not doing physical activity?**
Yes	**No**	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
Yes	**No**	**5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?**
Yes	**No**	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
Yes	**No**	**7. Do you know of any other reason you should not do physical activity?**
Yes	**No**	**8. Has your doctor ever told you that you have diabetes?**
Yes	**No**	**9. Has your doctor ever told you that you have high blood pressure?**
Yes	**No**	**10. Has your doctor ever told you that you have high cholesterol?**
Yes	**No**	**11. Has your doctor ever told you that you have high blood sugar?**
Yes	**No**	**12. Do you smoke?**
Yes	**No**	**13. Are you currently inactive?**
Yes	**No**	**14. Do you have a father, brother or son with heart disease before the age of 55 years old or a mother, sister or daughter with heart disease before the age of 65 years old?**

15. Measure height and weight to determine BMI:
Height:________
Weight:________

Participant Signature	**Date**

Note to ParQ Reader:

A “yes” to any Question 1-8 will eliminate the individual from participation.
A “yes” to 2 or more of Questions 9-14 indicates > low risk.
#15: If over 30 kg/m^2, the individual may have the risk factor of obesity.

APPENDIX E

Preliminary Survey

Name: Date:
Age:
Average days run per week over the last 6 months:
Average miles per week over the last 6 months:
Best race times in the past year (fill out one or more of the following):

1500m
5000m
10000m

Circle Yes (Y) or No (N)

Are you familiar with (have you heard about) lower leg compression sleeves/socks?	Y	N
Have you seen runners wear lower leg compression sleeves/socks?	Y	N
Do you personally know anyone who has worn lower leg compression sleeves/socks?	Y	N
Have you ever worn lower leg compression sleeves/socks?	Y	N
Do you believe lower leg compression sleeves/socks aid in any of the following:		
Training?	Y	N
Competitive performance?	Y	N
Recovery?	Y	N

APPENDIX F

Curriculum Vitae

Abigail S. Laymon

1025 E. Seventh St.
School of Health, Physical Education, & Recreation
Indiana University
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Education

2007-Present Indiana University, Bloomington, IN
Master of Science
Department of Kinesiology, School of Health, Physical Education, & Recreation
Majors: Exercise Physiology
Cumulative GPA: 3.897

2003-2007 DePauw University, Greencastle, IN
Bachelor of Arts, *Cum Laude*
Major: Kinesiology, Minor: Biochemistry

Professional Experience

Indiana University
2007-Present Associate Instructor, Department of Kinesiology
Columbus Regional Hospital
2006 Intern to the Wellness Program Director

Major Research

1. Effects of Altitude Training on Ventilatory, Metabolic, and Mechanical Characteristics in Elite Distance Runners. Indiana University Department of Kinesiology, Human Performance Laboratories. 2007-2008.
    a. Assisted in developing the research design.
    b. Worked in all facets of the data collection process.
    c. Analyzed gait variables data for interpretation.
2. RPS Actiped Intervention. Indiana University Department of Kinesiology. 2008.
    a. Coordinated and scheduled health screenings for Indiana University Residential Programs and Services employees.
    b. Assisted in data collection of anthropometric measures.
    c. Developed weekly step goals for the subjects.
    d. Entered physiological and survey data for interpretation.
3. Post-Exercise Recovery Refueling Knowledge, Behavior and Attitudes of Athletes. Indiana University Departments of Kinesiology and Applied Health Science. 2007-2008.
    a. Contacted race and event directors at sites throughout the state of Indiana in regards to participation in the study.
    b. Coordinated and assisted in the collection of survey data.
    c. Entered and analyzed data for interpretation.

Professional Interests
Human performance in high-level athletes, with particular regard to acute and chronic adaptations to environmental stress and exercise.

Abstracts
1. Laymon, A.S., Lundgren, E.A., McKenzie, J.M., Wilhite, D.P., Chapman, R.F. (2009). Running economy changes after altitude training: role of running mechanics. *Medicine & Science in Sports & Exercise*, 41(5), 320.
2. Wilhite, D.P., Laymon, A.S., McKenzie, J.M., Lundgren, E.A., Chapman, R.F. (2009). Maximal oxygen consumption changes after altitude: role of ventilatory acclimatization. *Medicine & Science in Sports & Exercise*, 41(5), 320.
3. Lundgren, E.A., Wilhite, D.P., Laymon, A.S., McKenzie, J.M., Chapman, R.F. (2009). Running economy changes after altitude training: role of ventilatory acclimatization. *Medicine & Science in Sports & Exercise*, 41(5), 320.
4. Chapman, R.F., McKenzie, J.M., Wilhite, D.P., Laymon, A.S., Lundgren, E.A. (2009). Measurement of gait in elite distance runners using fast sampling accelerometers. *Medicine & Science in Sports & Exercise*, 41(5), 320.
5. Troxell, C.L., Johnston, J.D., Hornsby, W.E., Laymon, A.S., Massey, A.P. (2009). The effects of a multi-level physical activity and health promotion intervention on a group of females in the worksite setting. *Medicine & Science in Sports & Exercise*, 41(5), 320.
6. Laymon, A.S., Johnston, J.D., Lindeman, A.K., Mickleborough, T.D., Stager, J.M. (2008). Post-exercise recovery refueling knowledge, behavior and attitudes of athletes. *Medicine & Science in Sports & Exercise, 40(5)*: S399-S40.

Manuscripts in Preparation
1. Chapman, R.F., Laymon, A.S., Wilhite, D.P., McKenzie, J.M., Tanner, D.A., & Stager, J.M. (2009) Characterization of gait and metabolic cost in elite male and female distance runners using fast sampling accelerometers.

Honors and Awards
1. Lucile M. Swift – Mona M. Russell Scholarship. Indiana University School of Health, Physical Education, and Recreation. 2009. $1500.
2. John R. Endwright Scholarship. Indiana University School of Health, Physical Education, and Recreation. 2009. $500.

Funded Extramural and Intramural Grants
1. Indiana University School of Health, Physical Education, and Recreation Research Council Travel Award. PI: A.S. Laymon. 2008. $150
2. Indiana University School of Health, Physical Education, and Recreation Department of Kinesiology Travel Award. PI: A.S. Laymon. 2008. $150.
3. Indiana University School of Health, Physical Education, and Recreation Research Council Travel Award. PI: A.S. Laymon. 2009. $200
4. Indiana University School of Health, Physical Education, and Recreation Department of Kinesiology Travel Award. PI: A.S. Laymon. 2009. $200.

Technical and Testing Experience

1. Measured gait variables during running using fast sampling accelerometers.
2. Executed metabolic rate testing with metabolic carts and Douglas bags.
3. Determined pulmonary function and ventilation during rest and exercise using metabolic carts, spirometers, and dry gas meters.
4. Assayed biological markers in blood and urine using ELISA kits and spectrophotometers.
5. Tested anaerobic capacity by means of performance tests.
6. Assessed body composition using hydrostatic weighing, skinfold thickness, and bioelectrical impedance analysis.
7. Determined changes in core and skin body temperature during rest and exercise in an environmental chamber using thermocouples and rectal probes.

Professional Teaching Experience

Indiana University

a. Exercise Physiology Laboratory. Department of Kinesiology, School of HPER. 2008-Present.
b. Fitness & Jogging. Department of Kinesiology, School of HPER. 2007-Present.
c. Personal Fitness Laboratory. Department of Kinesiology, School of HPER. 2008.